National Aeronautics and Space Administration

Rising Tides

$$6CO_2 + 2H_2O \xrightarrow{\text{LIGHT}} C_6H_{12}O_6 + 6O_2 + 6H_2O$$

CoastalObs Project
Education and Public Outreach Office
Hydrospheric and Biospheric Sciences Laboratory
NASA Goddard Space Flight Center
Wallops Flight Facility
2007

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www.nasa.gov

Cover Image Caption: The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) ocean color image of the Chesapeake Bay region and beyond. (Image courtesy of the SeaWiFS Project and GeoEye)

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Dear Teachers,

Welcome to *Rising Tides,* a collection of current research articles for high school and introductory college courses, complete with related activities. The activities were created to complement science courses—specifically biology, and marine and environmental sciences—but can be easily tied to chemistry and physics, and contain a strong mathematical and engineering component. They are also very applicable to cross-curriculum or interdisciplinary lessons. Important skills, such as critical thinking and data analysis, can be enhanced through these articles and activities.

How can you use *Rising Tides* with your classes? Here are some suggestions: students can write reviews of articles, use the information to fuel class debates, or use them as pre-lab activities for oceanography-related field trips.

Use *Rising Tides* to complement and reinforce lessons involving scientific research and inquiry, identifying organisms, microscope skills, scientific notation, classification, binomial nomenclature, interactions between organisms and environment, phytoplankton, marine science, photosynthesis, cellular respiration, global warming, and ecosystems.

Rising Tides can also support student understanding of important topics such as the properties of water, carbon cycle, water cycle, food chains/webs, abiotic and biotic factors, diversity, succession, trophic levels, niche, and how natural—as well as man-made—factors affect environments and populations.

NASA and its collaborators need your feedback. Please take a few moments to complete and return the survey located in the back of this journal. In addition, I strongly encourage you to have your students complete the student version of the survey, which is also included. This information is very important to us and will help improve future editions of the journal. Information on where to return the surveys is provided below.

We hope you enjoy this premier issue of Rising Tides and look forward to hearing from you!

Cordially,

Tiffany A. Moisan, Ph.D.

Please mail the completed forms to:

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Preface Figure Captions:

Near right: SeaStar satellite carrying SeaWiFS sensor. (Image courtesy of the NASA GSFC Scientific Visualization Studio. http://svs.gsfc.nasa.gov)

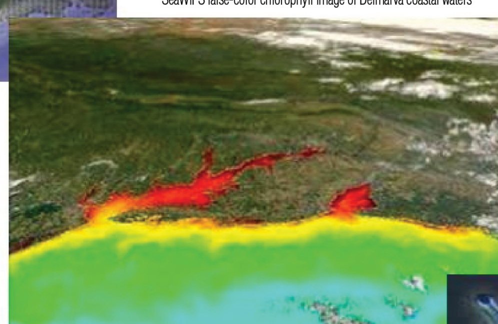
Middle right: SeaWiFS false-color chlorophyll image of the Delmarva coastline. (Image courtesy of SeaWiFS and GeoEye)

Far right: *Protoperidinium oblongum* phytoplankton cell. (Image courtesy of the Station Biologique de Roscoff, CNRS and UPMC).

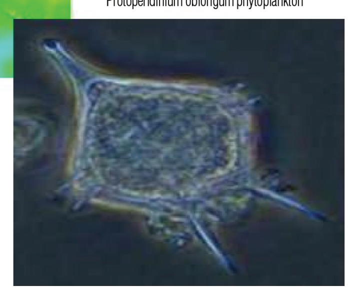
This premier issue of *Rising Tides* starts big by examining some of the latest National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) research related to large-scale oceanographic processes. Studying questions that involve large spaces (spatial) or periods of time (temporal) is challenging. Explore and discover the many ways scientists are meeting these challenges. “Ocean Watch” describes how scientists have established a coastal observatory. Such an observatory can be used to design a study that could not be addressed on a single research cruise or with a simple sampling scheme. One current issue that could be addressed using a coastal observatory is climate change. Global warming is a topic that has recently been in the news. In order to understand how anthropogenic CO_2 could influence climate, scientists must first study how carbon moves through the terrestrial and oceanic environments. There are still unanswered questions concerning the carbon cycle in the ocean. The role of very small phytoplankton (picophytoplankton) in the coastal carbon cycle is not well understood and the movement of dissolved carbon through coastal waters is still being researched. “Good Things Come in Small Packages” and “The Coastal Ocean Carbon Cycle from Space” explain some of what is known about picophytoplankton and dissolved carbon, respectively, and describe future research directions. Another recent topic in the news is harmful algal blooms. A very large bloom occurred last summer off the coast of New England. The extensive spatial scale made it obvious that small scale sampling could not adequately cover the bloom. Coastal observatories should be immensely helpful in increasing our knowledge of harmful algal blooms on the appropriate scales. “What is a Harmful Algal Bloom?” describes the many different types of harmful algae blooms that can occur. Used together, these articles will hopefully encourage students to think about the ocean on many different scales (from tiny picophytoplankton to global movements of carbon) and show them some exciting new research in oceanography.

SeaStar satellite carrying SeaWiFS

SeaWiFS false-color chlorophyll image of Delmarva coastal waters

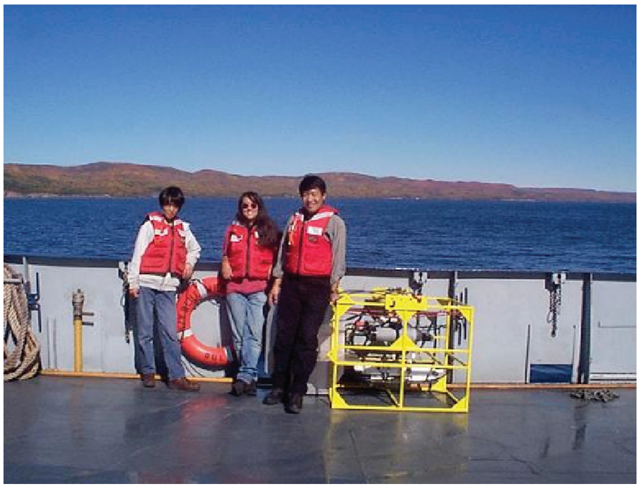


Protoperidinium oblongum phytoplankton



NOTES:

This section will give teachers and students the chance to get "up close and personal" with the many scientists and education personnel associated with this journal. It will feature a discussion on current NASA projects, as well as a few non-scientific questions.



Dr. Tiffany A. Moisan (center) on an oceanographic cruise on Lake Superior aboard the R/V *Blue Heron*.

Brian Campbell: *What and where is your current research position?*

Tiffany Moisan: I am a Researcher at the NASA Goddard Space Flight Center and am responsible for the Phytoplankton Photophysiology Laboratory. It is located on the Eastern Shore of Virginia, which is home to beautiful wildlife and a wonderful quality of life.

BC: *Why did you decide to become a scientist?*

TM: I've wanted to be a scientist ever since I was a young girl. I remember looking through shell books and I've always loved the ocean. I became really serious about science during my undergraduate education at Texas A&M University where I worked in an oceanographic laboratory for four years. It was then that I decided to become a phytoplankton ecologist and pursue higher degrees, including a Master's (Old Dominion University) and a Ph.D. (Scripps Institution of Oceanography, University of California). During that time, I went to the Antarctic to study phytoplankton and was able to see penguins and whales and all sorts of beautiful wildlife.

BC: *What are some of the major projects you have worked on?*

TM: My major project that I am currently working on is the Biophysical Interactions in Coastal Margin Ecosystems (BIOME) program, which has several scientists and educators working on it from Virginia, Maryland, New Jersey, and Pennsylvania. It has several facets about it that address different temporal and spatial scales. We utilize seasonal oceanographic cruises along the Delmarva Peninsula studying the biology, chemistry, and physics of the region. We also have biweekly cruises off the coast of Virginia at the Wallops Flight Facility. We will be using NASA ocean color satellites to overlook the area that spans out into the Atlantic Ocean and also NOAA sea-surface temperature satellites. Our surface autonomous vehicle, affectionately called OASIS (Ocean Atmosphere Sensor Integration System) will traverse waters in the area, giving real-time data like the weather forecaster does on TV.

BC: *What are your current projects?*

TM: Scientists must acquire money from funding agencies such as NASA, Office of Naval Research, National Science Foundation, and others. We currently have the BIOME Project funded through NOAA and NASA. We also have an educational project funded through NASA that is responsible (with NOAA) for funding this journal.

BC: *What does NASA have to offer the oceanographic community?*

TM: NASA contributes a tremendous and valuable data set—called "ocean color"—to the oceanographic community. Ocean color is the characteristic hue of the ocean according to the presence and concentration of specific minerals or substances, such as chlorophyll. Together with global or regional maps of pigment distribution of phytoplankton all over the world and other products, NASA gives unprecedented global coverage of phytoplankton information to scientists and the public. NASA also has Earth scientists who study the ocean using satellites and who look at things like colored dissolved organic matter, ocean biology, calibration of the satellite, modeling of the physics of the ocean, etc. Check out our Web site at www.nasa.gov. We have a great team of people working on Earth science.

BC: *On a more personal note, what are some of your hobbies?*

TM: My main hobby is my children: four-year-old Katie, and one-year-old, Alyssa, who keep me jumping and running around. We do yoga together! I also love gourmet cooking, growing orchids, biking, and swimming as well.

BC: *Where are your favorite travel destinations (for work or pleasure)?*

TM: Work has taken me all over the world and I've had a blast traveling. I've been to the Antarctic Ocean during austral winter[1] where I saw many Adélie penguins and Minke whales. The icebergs were incredible and each had something unique. I lived on the continent of Antarctica in McMurdo Sound, spending Christmas and New Year's Day there. I had a great time there, too. I went camping in the Dry Valleys while on an expedition to Lake Fryxell. I flew around in helicopters and sampled the ocean and even landed on an iceberg and went hiking on it!!!

BC: *What would you tell our young students wishing to pursue a career in oceanography at NASA?*

TM: Reach for the stars and give it your best shot. Be conscious about learning and fostering both your creativity and your skills. Learn to take criticism constructively. Embarking on a career in science requires a lot of dedication and schooling. I think the best advice that I've gotten in my life is "Don't rote memorize—learn concepts and ideas!" The sciences are becoming very interdisciplinary and cross cutting between each. You no longer do just "biology," but instead, you focus on the relationship between biology and chemistry or physics. It is best to take as many science classes that your can fit into your schedule. Also, it is important to have a good background in mathematics and programming. Choose your career based on how much fun you have—all will come naturally after that.

1 Winter in the Southern Hemisphere.

Tiffany Moisan

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…*"I hope you still feel small when you stand beside the ocean…"* (Lee Ann Womack)

These lyrics from a recent song express a sentiment that many people have felt. Standing on the beach, the ocean seems to stretch on forever. Its shear size is amazing, covering 71% of the Earth's surface. Its enormous size is what draws people to the ocean and inspires them, but it is also what makes the ocean so difficult to study. The National Oceanic and Atmospheric Administration (NOAA) is trying to tackle this problem by establishing a coastal observatory project.

NOAA's plan is to fund oceanographic observatories along the entire coast of the United States. These observatories will track changes in biology, chemistry, and physics in the oceans, looking for variation in both space and time. One area that lacked an observatory was the Delmarva Peninsula (coastal Virginia, Maryland, and Delaware; Figure 1). This is an important region to study as the Chesapeake Bay, the largest estuary in the United States, empties into the ocean here. Delmarva's watershed and airshed are influenced and significantly impacted by urban (Washington, D.C.; Baltimore, MD; Philadelphia, PA; Hampton Roads, VA; and Wilmington, DE) and agricultural (farming, fisheries, and the related poultry industry) practices, all of which affect the coastal ocean. Scientists want to improve their understanding of the impact of a large coastal bay on the movement of water and chemicals into the coastal ecosystem. How might increased pollution, changes in freshwater flow, or warming due to climate change impact this area? Scientists hope that an observatory might be able to help answer these questions.

One question, in particular, that scientists are interested in is the impact of increased nutrient pollution on the coastal oceans. Rivers from six states drain into the Chesapeake Bay. The watershed is primarily farmland and forest. Runoff from farmland is often high in nutrients, particularly nitrogen and phosphorus, from fertilizers. This process is termed eutrophication, which is the over-abundance of available nutrients in aquatic ecosystems. When these nutrients enter the Chesapeake Bay they can cause increased growth of phytoplankton.

Phytoplankton are single-celled organisms that photosynthesize and live in fresh and salt water. Just like plants on land, phytoplankton need both light and nutrients to grow, so an increase in nutrients can quickly lead to increased growth. An overabundance of phytoplankton growth decreases light penetration through the water to submerged aquatic vegetation (SAV). This in turn decreases available oxygen produced through photosynthesis by SAV in the water, which can be detrimental to animals and plants in the water thereby negatively affecting the ecosystem as it depletes the oxygen content. Water from the Chesapeake Bay then flows into the coastal oceans. Are the nutrients still high at the mouth of the bay or have they been used up by the phytoplankton? If there are still nutrients left, how do the phytoplankton in the ocean respond to the nutrients? How far from the mouth of the bay are increased nutrients found? Do all phytoplankton respond the same or do some species increase in numbers while others decline? Does this effect change with the seasons, between years, or with the occurrence of hurricanes or winter storms? These questions are too complex and the temporal and spatial scales too large to answer with a single set of measurements.

The main obstacle is how to comprehensively study an area this large on a limited budget. The Wallops Coastal Ocean Observation Laboratory (WA-COOL), a group of scientists from the mid-Atlantic states, joined together to try and tackle this problem. They developed a plan that combined established methods with the development of new technologies. Every method has benefits and drawbacks, but by using a variety of approaches, they hope to be able to address some of these large-scale questions.

Figure 1. Carla Makinen, part of the CoastalObs Science Team, aboard the R/V *Cape Henlopen* as part of the BIOME project.

Satellites

One approach is to collect data from satellites, which can capture an image of the entire study area in seconds essentially every day, provided that the skies are cloud-free throughout the year. Ocean color sensors are instruments used to estimate the amount of phytoplankton by analyzing the color of the water (Figure 2a). Imagine flying in an airplane. You couldn't see a single blade of grass on the ground, however, if there was a field of grass, you could identify it by its green color (Figure 2b). Ocean color sensors work by the same principle. They can't see the individual phytoplankton cells, however, all phytoplankton have chlorophyll, just as all plants do. The more phytoplankton in the water, the greener the water becomes. The drawback to satellites, however, is that they can only observe the surface of the ocean. Just as people can't see deep into the ocean, neither can satellites.

Ocean color sensors, such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiomenter (MODIS), can help address the impact of nutrients on coastal waters by estimating the amount of phytoplankton in the entire Delmarva region on a daily basis. If there is a surprise event, such as a storm, excess nutrients may be washed into the Chesapeake Bay and out into the coastal ocean. Given the unpredictable nature of a storm, it may not be possible to arrange a boat to go out and sample to measure the impact. By studying the satellite images over the next several days or weeks, any effects can be noted. In addition, satellite data goes back many years. The first ocean color sensor, Coastal Zone Color Scanner (CZCS), was launched in 1978; thus, interannual variability can be investigated.

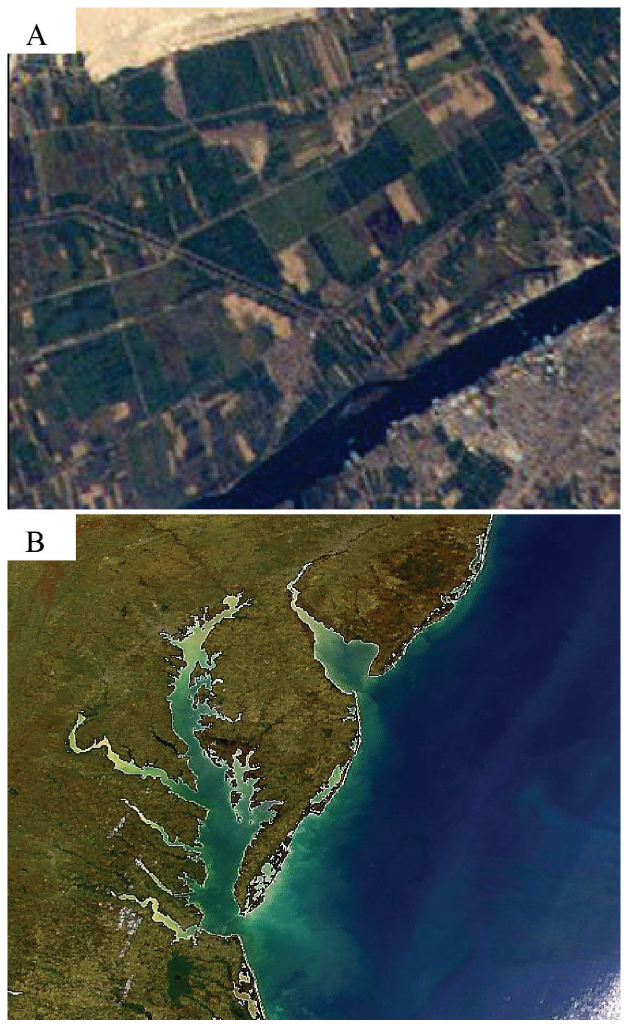

Figure 2. (a) Photo from airplane. Note the green regions where crops are growing. (b) SeaWiFS ocean color image of the Chesapeake Bay region and beyond. (Image Courtesy of SeaWiFS and GeoEye)

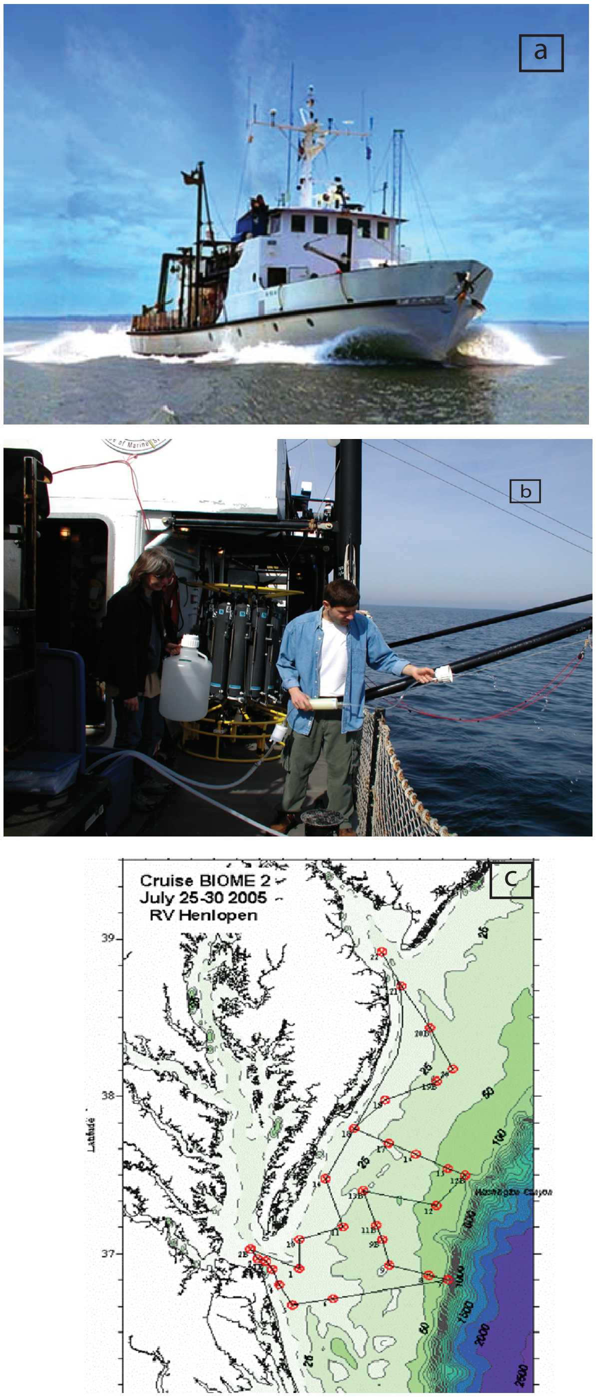

Figure 3: (a) The University of Delaware's research vessel, R/V *Cape Henlopen.* This research vessel is used by WA-COOL to study the Delmarva Peninsula. (b) Scientist, Antonio Manino, collecting water on a research cruise. (c) This is a typical cruise track along the Delmarva Peninsula. It covers the entire region between Delaware Bay and Chesapeake Bay. On this cruise, about 29 stations were sampled. The colored region is the topography of the bottom of the ocean.

Research Vessels

Research vessels allow the for most in-depth measurements, as scientists can collect and analyze water samples in great detail from all depths (Figures 3a and 3b). They can investigate the organisms, measure environmental data, and run experiments in a way not afforded by any other approach. The largest drawback of boats is their cost (approximately $10,000 per day) and the relatively poor spatial coverage (they only steam ~15 miles per hour). A typical cruise track for a 3-day cruise in the Delmarva region is shown in Figure 3c. At the end of three days, very detailed data can be collected, but only from a limited number of widely separated points in the ocean (in this case, about 29 stations).

Performing short cruises on a research vessel 3–4 times a year, through the Bio-Physical Interactions in Coastal Margin Ecosystems (BIOME) program, is essential to link changes in nutrients along the Delmarva coast with changes in phytoplankton. Cruises provide an opportunity to actually measure nutrients (nitrate, ammonia, and phosphate) with a high degree of accuracy. They are also the only way to sample the phytoplankton to determine which species are present at varying locations, at multiple depths, and in different seasons.

Coastal Ocean Bio-optical Buoy (COBY)

The scientists from WA-COOL have designed a new buoy (Figure 4), which will be deployed off the coast of Virginia to aid in coastal observation. A profiling mechanism will lower a suite of instruments to predetermined depths within the water column at desired time intervals to take measurements. Several instruments will also be positioned above the water surface on the buoy. The above-water instruments will measure the standard suite of meteorological variables (air temperature, relative humidity, wind velocity, and atmospheric pressure). In addition, an above-water ocean color sensor will take measurements similar to the ocean color satellite. These instruments will gather valuable data throughout the water column throughout the year, but at only the selected locations.

Several of the instruments on this buoy will be useful for monitoring phytoplankton and nutrients in the shelf waters including the following:

Fluorometer

When chlorophyll absorbs light, the energy from the light is directed in three ways. Some light is used for photosynthesis, some is released as heat, and a very small percentage is reemitted as red light (fluorescence). A fluorometer is able to measure how much light is emitted from a water sample. This information can be used to estimate the amount of chlorophyll-containing organisms in the sample. This fluorescence data is the easiest way to estimate the amount of phytoplankton in the water when scientists can not be present to actually count them.

Figure 4. COBY is a new buoy that WA-COOL designed to continuously monitor the Delmarva coastal waters.

Nitrate Sensor

A nitrate sensor is an absorption meter for ultraviolet light that is specifically designed to find the absorption of nitrate ions in the water and calculate the concentration. Nitrate ions are one of the most abundant nutrients used by phytoplankton. This makes it one of the easiest nutrients to measure, and will tell whether the phytoplankton have enough nutrients to grow.

Acoustic Doppler Current Profiler (ADCP)

The ADCP instrument is placed in the water and uses sound waves to measure the direction and speed the water is moving at every depth. The data collected by the ADCP can be used to determine how the water circulates and how nutrients, phytoplankton, and water masses move from one location to another.

Ocean Atmosphere and Sensor Integration System (OASIS)

OASIS is a brand new type of vehicle that is being designed by the WA-COOL scientists. It is an unmanned boat that can be equipped with oceanographic instrumentation and programmed to cruise around the study area for long periods of time (Figure 5). Because these OASIS vehicles are autonomous (unmanned), they can be sent out to gather data, while the scientists continue other research in the lab or on research cruises. There are controls, similar to those for video games, that can be used to control OASIS or a track can be pre-programmed for OASIS to follow. The system is designed so that if winds or waves cause OASIS to turn over, the vehicle will right itself. OASIS can be sent into harsh conditions that would be too dangerous for research vessels. For example, sometimes research cruises can be delayed or stopped by storms and high winds. OASIS, however, can be sent right into the winds, or even into hurricanes, to see how properties might change during these severe events. Because OASIS is unmanned, the number of measurements that can be made is limited, and as new technologies are developed the amount of data that can be collected will continue to expand.

Figure 5: OASIS is a vehicle that can be sent out into the ocean unmanned to investigate interesting phenomenon or to monitor certain regions in the ocean. It has particular potential to help investigate phytoplankton blooms or storms that may be difficult to monitor with other methods.

A vehicle like OASIS would be invaluable for following up if a phytoplankton bloom (large numbers of phytoplankton) were found along the Delmarva coast in response to high nutrient levels. A bloom of phytoplankton may be identified by satellite or on a research cruise. A satellite, however, can only return data about phytoplankton concentration and research cruises occur for a very limited time. OASIS could be sent to the region to take more detailed measurements for as long as was needed to understand the fate of the nutrients and phytoplankton.

Working alone, a scientist would have great difficulty addressing a complex question such as how nutrients impact the coastal waters off the Delmarva Peninsula. Using an ocean observatory, such as WA-COOL, would allow a scientist to combine the large-scale monitoring of a satellite, with the detailed data collection from a research vessel, the high temporal resolution of a buoy, and the flexibility of an unmanned vehicle, such as OASIS, and present a more comprehensive view of the region.

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Glossary

Airshed—part of the atmosphere that behaves in a coherent way with respect to the dispersion of emissions.

Eutrophication—the process by which a body of water becomes enriched in dissolved nutrients that stimulate the growth of phytoplankton and aquatic plants often resulting in the depletion of dissolved oxygen.

Fluorescence—light emitted from an object or substance after it has absorbed light at a different wavelength.

Nitrate—NO_3^-, a compound that contains nitrogen and oxygen that comes from decomposing organic materials like manure, plants, and human waste.

Watershed—the region draining into a river, river system, or other body of water.

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Additional Reading:

M. Carlowicz, "Going wireless in the deep blue," *Oceanus,* vol. 45, 2006.

M. Carlowicz, "Scientists gear up to launch ocean observatory networks," *Oceanus,* vol. 45, 2006.

Both of the above articles can be accessed at:
http://www.whoi.edu/oceanus/index.do

Web Sites:

http://ocean.wff.nasa.gov/biome1/

The BIOME Web site that accompanies this journal has links to many of the instruments that are being used as part of WA-COOL. There is a picture of each of the instruments and a short description of what each instrument does.

https://www.coastalobs.us/

The CoastalObs Web site has an in-depth description of the observing program off the Delmarva Peninsula.

Discussion Questions:

1. Discuss three purposes of monitoring coastal waters.
2. What nutrients and conditions mentioned in the article create optimal growth conditions for phytoplankton?
3. Using your knowledge of food webs, describe two positive and two negative contributions phytoplankton make to the environment.
4. List three of the instruments used by WA-COOL and the importance of their specific measurements.
5. Discuss the importance of phytoplankton in ecosystems. (Hint: One way to understand the importance of phytoplankton is to examine what the effects would be of taking it out of the ecosystem.)

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When most people think about life in the ocean, they think of large organisms such as whales, fish, and sea turtles. However, scientists also study life on the opposite end of the size spectrum—some of the smallest organisms in the ocean. Phytoplankton are single-celled organisms in the ocean that photosynthesize. Picophytoplankton are the smallest of the phytoplankton, less than 2–3 micrometers (μm) in size. To appreciate how small this is, we can compare it to the size of a single grain of sand (Figure 1). A normal phytoplankton cell might be 30 μm in size, a third the size of a grain of sand. A picophytoplankton cell can be 100 times smaller than a single grain of sand!

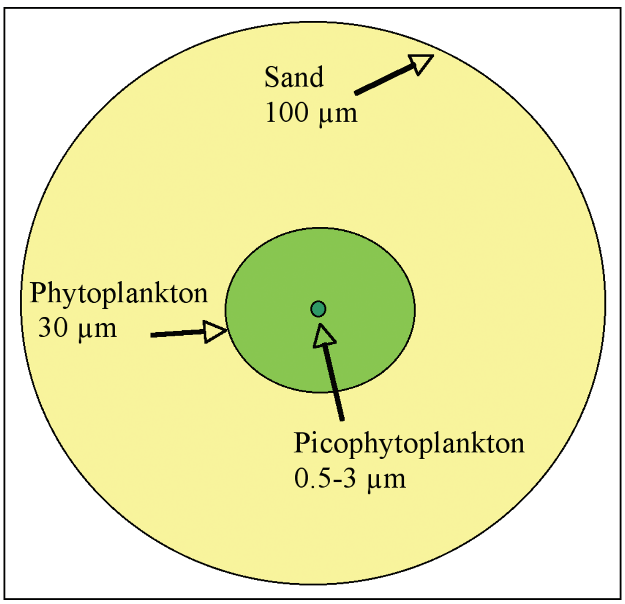
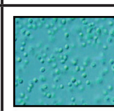
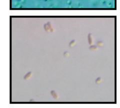
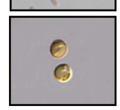


Figure 1. Comparison of the size of a grain of sand, a typical phytoplankton, and a picophytoplankton.

There are both advantages and disadvantages to being so small. The most important benefit is that small cells can acquire resources more easily. Phytoplankton need light and nutrients, just like plants on land. Their small size means they are more likely to be photoinhibited (exposed to too much light) and they have less available space to store nutrients. The advantages of a small size, however, appear to outweigh the disadvantages [1].

Picophytoplankton can be either prokaryotic (simple, without a nuclear membrane) or eukaryotic (complex, with a nuclear membrane). The prokaryotic picophytoplankton are dominated by two genera, *Prochlorococcus* and *Synechococcus*. Both were discovered relatively recently—*Synechococcus* in 1979 [2], and *Prochlorococcus* in 1988 [3]. Before these discoveries, the importance of picophytoplankton was not realized. *Prochlorococcus* is the smallest known photosynthetic organism and is thought to be the most abundant phytoplankton on Earth (Table 1; see review [4]). *Synechococcus* is a bit larger in size and is found from the North Pole to the South Pole (see review [5]).

TABLE 1
Comparison of Picophytoplankton

Type	Picture	Cell size (μm)	Cell number (cells mL^{-1})
Prochlorococcus		0.5–0.7	100,000
Synechococcus		0.6–1.6	
Picoeukaryote		0.8–2	

Much research has been done to understand *Prochlorococcus* and *Synechococcus* and their roles in the environment. For example, it is now believed that they contribute significantly to the amount of photosynthesis in the ocean [4, 5]. Researchers have even sequenced the complete genome from both [6, 7]. These discoveries have revealed an entire realm of organisms we did not even know existed and have revolutionized how we think about phytoplankton in the ocean.

The eukaryotic component of the picophytoplankton is very different. Often referred to as picoeukaryotes, they are larger in size and fewer in number than either of the prokaryotes (Table 1; [8]). They are also more diverse and much less studied. Currently, there are picoeukaryotes known from 10 algal classes, however, new species are being found each year. For much of the world, we don't know how many species there are, which are most common, how they are distributed, and how they change seasonally. We don't know what niches or roles they play in the environment, how much they photosynthesize, or who eats them. These are exciting questions that desperately need to be studied.

Measuring Diversity

One of the primary reasons that relatively little research has been done with picoeukaryotes is the difficulty associated with identifying them. Traditionally, phytoplankton have been identified by distinguishing characteristics using a microscope, however, most picoeukaryotes are small, round, and green or brown in color (Figure 2). This makes them difficult or impossible to tell apart using a compound microscope, or even a more specialized research microscope (such as an epifluorescence or electron microscope). A phytoplankton cell can also be selected and grown in the lab in order to study a specific species in more detail. This method tends to be selective as some species grow better under a certain set of conditions (e.g., light, temperature, or nutrients). Most (90–99%) phytoplankton cannot be cultured in the laboratory. Those species that grow well in the lab are not always the same species that are found most often in the ocean [9]. Instead, scientists have been turning to molecular techniques to help investigate the diversity of picoeukaryotes.

These molecular techniques are based on knowledge that DNA sequences vary between different taxa (for example, different classes, genera, or even species). Often, the first step is to look for a section of DNA[1] that is unique to the organism or group of interest. Frequently, researchers use a gene that codes for a subunit of the ribosome (ribosomes are the machinery for making proteins). Because species have ribosomes, they all must have this gene. In eukaryotes, this gene is referred to as the 18S ribosomal RNA[2] gene. For example, if a phytoplankton cell had the sequence ACG TCC TTG TTC GAC GCT[3] in its 18S RNA gene, you would know this species was in the class Pelagophyceae (Figure 3) as that sequence is unique to Pelagophyceae [10].

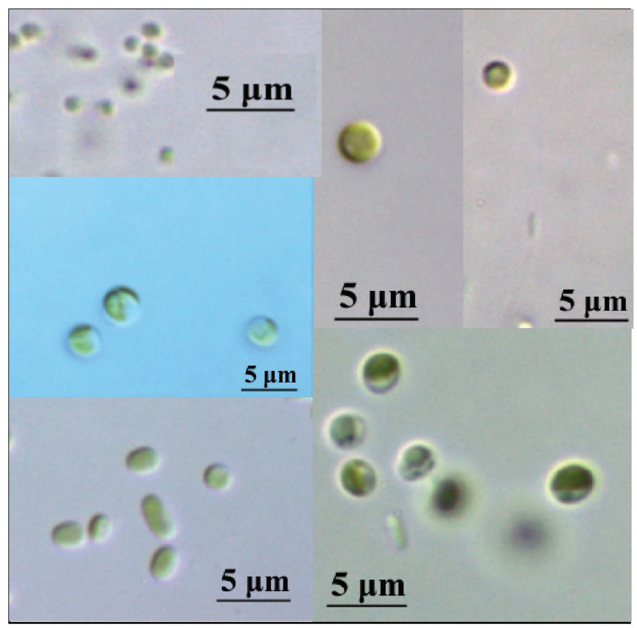


Figure 2. A variety of picoeukaryotes. Note the similar shape and color. (Pictures courtesy of Provasoli-Guillard National Center for Culture of Marine Phytoplankton—Bigelow Laboratory for Ocean Sciences)

1 DNA: deoxyribonucleic acid
2 RNA: ribonucleic acid
3 The major amino acid building blocks of DNA and RNA are Cytosine (C), Guanine (G), Adenine (A), and Thymine (T).

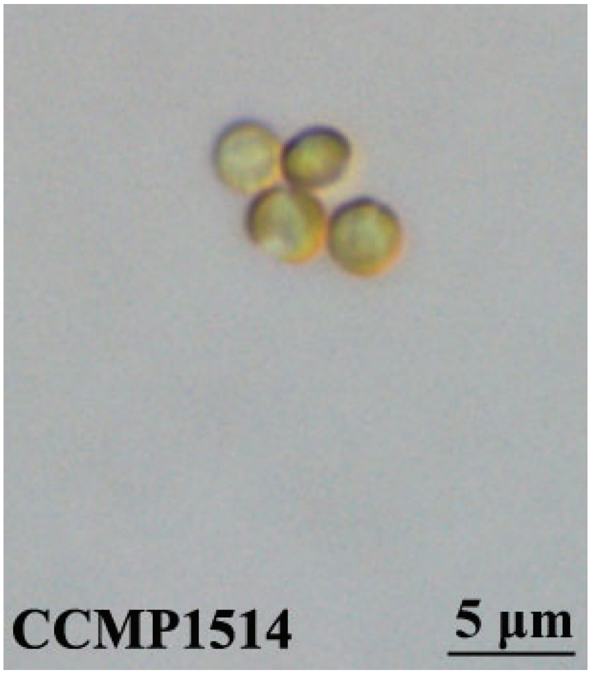


Figure 3. The class Pelagophyceae can be identified using molecular techniques by the sequence ACG TCC TTG TTC GAC GCT in its 18S RNA gene (Pictures courtesy of Provasoli-Guillard National Center for Culture of Marine Phytoplankton—Bigelow Laboratory for Ocean Sciences).

Once a researcher has decided on which segment of DNA they will use, there are several techniques they can employ to investigate the diversity in the ocean. Some researchers have created a "library" of a particular gene, like the 18S RNA gene discussed above. The library is used to catalog many of the picoeukaryote sequences found in a particular location [11, 12]. To create a library, DNA is extracted from the picoeukaryotes. A section of DNA is then inserted into a bacterium cell. As the bacteria reproduce, they make more and more copies of the sequence. The section of DNA can then be isolated from the bacteria and sequenced. This can be repeated many times until a collection of DNA sequences exists in the library. This technique gives scientists many sequences from the environment, but it is also time consuming and there are some biases.

An alternative is to get a snapshot view of the entire picoeukaryote community using a procedure called denaturing gradient gel electrophoresis (DGGE) [13, 14]. In this method, DNA from the environment is amplified so there are many copies. The DNA is broken down, or denatured, by a gradient of chemicals in a gel. DNA with different sequences will break down at different times, leaving a series of bands on the gel (Figure 4). Each of the bands corresponds to a different sequence and thus, different taxa. The bands can be cut out and sequenced, then compared to known species. The major advantage of this technique is that it is possible to run several samples on a single gel to compare different locations, depths, or seasons.

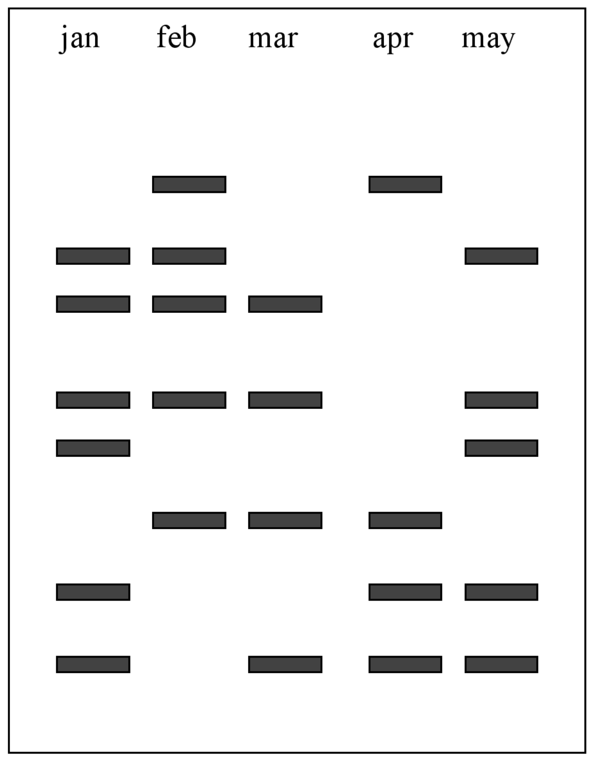


Figure 4. An example of a hypothetical DGGE gel. Individual bands represent unique DNA sequences. In this example, there are samples shown from five months. In January, six different taxa were found, while in March, only four taxa were found.

A final method used to investigate diversity is to design probes that are specific to picoeukaryote groups [15]. The probes are small segments of DNA that can be added to a sample. The probes attach to cells that have complementary segments of

DNA. When put under a special microscope, the cells glow and can be counted. This technique, called fluorescent *in situ* hybridization (FISH), is the only method that allows a researcher to count how many cells of a particular species are in a sample.

Several molecular studies have been completed from the Pacific [12, 16], Southern Ocean [11, 17], North Atlantic [11], Mediterranean Sea [11, 9], and English Channel [18]. All studies noted that a single class of picoeukaryotes, Prasinophyceae, made up a large portion of the phytoplankton sequences retrieved. In some cases, a single genus dominated the samples collected [19]. Sequences from a number of other classes were also frequently found. For example, prymnesiophytes seem to be very important in the open ocean, but there is much less data from these regions as they are much harder to study than the coasts [12]. There are many places around the world where the picoeukaryote diversity has not been examined. Will new areas also be dominated by a single class or picophytoplankton? Or will we discover greater diversity as we continue to investigate new locations? Picoeukaryotes are an expanding area of study. In the next several years, there will undoubtedly be a number of studies that will enlarge our knowledge and may even revolutionize how we think of picoeukaryotes and their role in the environment.

Acknowledgments

I would like to thank several anonymous reviewers for reviewing this manuscript and Provasoli-Guillard National Center for Culture of Marine Phytoplankton—Bigelow Laboratory for Ocean Sciences for the use of the pictures of picoeukaryotes.

Additional Reading

E.F. Delong, "A plentitude of ocean life," *Natural History,* vol. 112, pp. 40–46, 2003.

S. Nadis, "Insights: The cells that rule the seas," *Scientific American,* vol. 289, pp. 52–53, 2003.

Web Sites

http://ccmp.bigelow.org

The Provasoli-Guillard National Center for Culture of Marine Phytoplankton—Bigelow Laboratory for Ocean Science. This site provides information on many of the picophytoplankton currently in culture (with pictures and molecular information when available) and also includes instructions for growing phytoplankton in a lab.

http://europa.eu.int/comm/research/news-centre/en/env/02-10-env01.html

European Research News Centre, "The Lilliputians of the Plankton World"—Much of the research on picoplankton has been completed by a group of European labs as part of the PICODIV program. This site provides an overview of their work.

http://www.jgi.doe.gov/whoweare/microbialgenome.html

DOE Joint Genome Institute, Microbial Genomic page—The genomes of two picophytoplankton, *Prochlorococcus* and *Synechococcus,* have been sequenced and this is the official Web site.

References

[1] J.A. Raven, "The twelfth Tansley lecture. Small is beautiful: the picophytoplankton," *Functional Ecology,* vol. 12, pp. 503–513, 1998.

[2] J.B. Waterbury, S.W. Watson, R.R. Guillard, and L.E. Brand, "Widespread occurance of a unicellular, marine planktonic, cyanobacteria," *Nature,* vol. 277, pp. 293–294, 1979

[3] S.W. Chisholm, R.J. Olson, E.R. Zettler, J.B. Waterbury, R. Goericke, and N. Welschmeyer, "A novel free-living prochlorophyte occurs at high cell concentrations in the oceanic euphotic zone," *Nature,* vol. 334, pp. 340–343, 1988.

[4] F. Partensky, W.R. Hess, and D. Vaulot, "Prochlorococcus, a marine photosynthetic prokaryote of global significance," *Microbiology and Molecular Biology Reviews,* vol. 63, pp. 106–127, 1999.

[5] J.B. Waterbury, S.W. Watson, F.W. Valois and D.G. Franks, "Biological and ecological characterization of the marine unicellular cyanobacterium Synechococcus," *Canadian Bulletin of Fisheries and Aquatic Sciences,* vol. 214, pp. 71–120, 1986.

[6] G. Rocap, F.W. Larimer, J. Lamerdin, S. Malfatti, P. Chain, N.A. Ahlgren, A. Arellano, M. Coleman, L. Hauser, W.R. Hess, Z.I. Johnson, M. Land, D. Lindell, A.F. Post, W. Regala, M. Shah, S.L. Shaw, C. Steglich, M.B. Sullivan, C.S. Ting, A. Tolonen, E.A. Webb, E.R. Zinser, and S.W. Chisholm, "Genome divergence in two *Prochlorococcus* ecotypes reflects oceanic niche differentiation," *Nature*, vol. 424, pp. 1042–1047, 2003.

[7] B. Palenik, B. Brahamsha, F.W. Larimer, M. Land, L. Hauser, P. Chain, J. Lamerdin, W. Regala, E.E. Allen, J. McCarren, I. Paulsen, A. Dufresne, F. Partensky, E.A. Webb, and J. Waterbury, "The genome of a motile marine Synechococcus," *Nature,* vol. 424, pp. 1037–1042, 2003.

[8] W.K.W. Li, and T. Platt, "Photosynthetic picoplankton in the ocean," *Science Progress,* vol. 71, pp. 117–132, 1987.

[9] R. Massana, V. Balagué, L. Guillou, and C. Pedrós-Alió, "Picoeukaryotic diversity in an oligotrophic coastal site studied by molecular and culturing approaches," FEMS *Journal of Eukaryotic Microbiology,* vol. 47, pp. 76–84, 2000.

[10] N. Simon, L. Campbell, E. Örnólfsdóttir, R. Groben, L. Guillou, M. Lange, and L.K. Medlin, "Oligonucleotide probes for the identification of three algal groups by dot blot and fluorescence whole-cell hybridization," *Nature,* vol. 334, pp. 340–343, 1988.

[11] B. Díez, C. Pedrós-Alió, R. Massana, "Study of genetic diversity of eukaryotic picoplankton in different oceanic regions by small-subunit rRNA gene cloning and sequencing," *Applied and Environmental Microbiology,* vol. 67, pp. 2932–2941, 2001.

[12] S.Y. Moon-van der Staay, R. De Wachter, and D. Vaulot, "Oceanic 18S rDNA sequences from picoplankton reveal unsuspected eukaryotic diversity," *Nature,* vol. 409, pp. 607–610, 2001.

[13] E.J. van Hannen, M.P. van Agterveld, H.J. Gons and H.J. Laanbroek, "Revealing genetic diversity of eukaryotic microorganisms in aquatic environments by denaturing gradient gel electrophoresis," *Journal of Phycology,* vol. 34, pp. 206–213, 1998.

[14] B. Díez, C. Pedrós-Alió, T.L. Marsh, and R. Massana, Application of denaturing gradient gel electrophoresis (DGGE) to study the diversity of marine picoeukaryotic assemblages and comparison of DGGE with other molecular techniques," *Applied and Environmental Microbiology,* vol. 67, pp. 2942–2951, 2001.

Glossary

Eukaryotic—pertaining to a complex cell with a nuclear membrane.

Niche—the ecological role of an organism within the community.

Photosynthesis—incorporation of CO_2 into organic molecules.

Prokaryotic—pertaining to a simple cell without a nuclear membrane.

Ribosome—the site of protein synthesis within a cell.

Taxa—a classification or grouping of organisms (i.e., kingdom, phylum, class, order, family, genus, species).

[15] F. Not, N. Simon, I.C. Biegala, and D. Vaulot, "Application of fluorescent in situ hybridization coupled with tyramide signal amplification (FISH-TSA) to assess eukaryotic picoplankton composition," *Aquatic Microbial Ecology,* vol. 28, pp. 157–166, 2002.

[16] A.Z. Worden, J.K. Nolan, and B. Palenik, "Assessing the dynamics and ecology of marine picophytoplankton: The importance of the eukaryotic component," *Limnology and Oceanography,* vol. 49, pp. 168–179, 2004.

[17] B. DÍez, R. Massana, M. Estrada, and C. Pedrós-Alió, "Distribution of eukaryotic picoplankton assemblages across hydrographic fronts in the Southern Ocean, studied by denaturing gradient gel electrophoresis," *Limnology and Oceanography,* vol. 49, pp. 1022–1034, 2004.

[18] K. Romari, and D. Vaulot, "Composition and temporal variability of picoeukaryote communities at a coastal site of the English Channel from 18S rDNA sequences," *Limnology and Oceanography,* vol. 49, pp. 784–798, 2004.

[19] F. Not, M. Latasa, D. Marie, T. Cariou, D. Vaulot, and N. Simon, "A single species, Micromonas pusilla (Prasinophyceae), dominates the eukaryotic picoplankton in the Western English Channel," Applied and Environmental Microbiology, vol. 70, pp. 4064-4072, 2004.

Jessica K. Nolan: Jessica Nolan completed her undergraduate degree at the University of New England in Biddeford, ME and her graduate work at Scripps Institution of Oceanography in La Jolla, CA. During her time as an undergraduate and graduate student, she had the amazing opportunity to travel around the world conducting research. She travelled to Alaska and twice to the Indian Ocean. Ms Nolan loves research cruises as they provide the opportunity to meet other researchers and see what they are doing, see all types of incredible organisms (from bioluminescent phytoplankton to whales), and explore the ecology and culture of a new country. She's currently an Assistant Professor of Biology at York College of Pennsylvania. Her main research interests involve picophytoplankton diversity, ecology, and optics; however, with her students, she's done research on a wide range of marine and freshwater organisms.

Objective:

The objectives of this activity are

1. to learn how to use a micrometer—a specialized slide that allows you to measure the field of view on a microscope,
2. to become familiar with phytoplankton and picophytoplankton,
3. to improve microscope skills, and
4. to utilize math skills

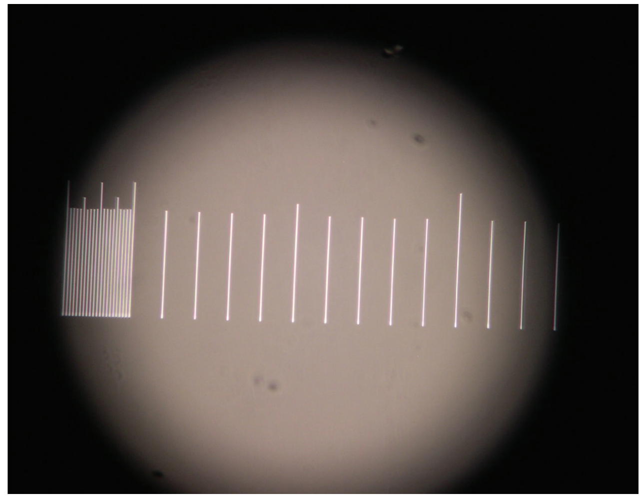


Figure 1: An example micrometer. The scale is inscribed in the round silver disk in the middle. In this case, the larger gradations are 0.1 mm, and the small gradations on the scale are 0.01 mm.

Materials:

- Microscope
- Stage micrometer (if a stage micrometer is unavailable, a small plastic metric ruler can be used or a variety of micrometers can be printed from the Web at: http://www.microscopy-uk.org.uk/mag/imgoct02/MicroscopeCalibrationRule.pdf)
- Slides / Cover slip
- Phytoplankton sample—a natural sample or a mixed assemblage bought from a lab supply company and a culture of picophytoplankton

Procedure:

1. Obtain a micrometer. The size of the scale or the gradations should be indicated on the micrometer (Figure 1).

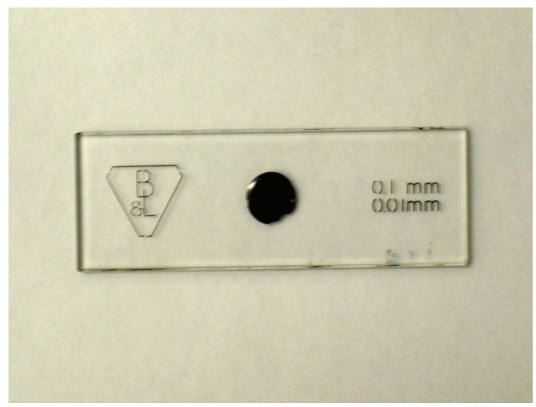


Figure 2: On this microscope, the field of view is 1.51 mm.

2. Place the micrometer under the lowest-power objective (likely 4 or 10x) and center the scale below the objective. Bring the scale into focus (Figure 2). What is the size of your field of view using the lowest-power objective? Measure this by determining the number of units on the micrometer visible under this objective.

Magnification of lowest-power objective:

____

Field of view using lowest-power objective:

____

3. Repeat the process for higher magnification if additional objectives are available.

Magnification of middle-power objective:

____

Field of view using middle-power objective:

____

Magnification of highest-power objective:

____

Field of view using highest-power objective:

____

The size of the field of view under higher magnification can also be computed mathematically. For example, if your field of view is 1.51 mm under 10x, then how big would the field of view be under the 40x objective?

1.51 mm x 10 = X mm x 40

(1.51 mm x 10)/40 = X mm

0.38 mm = X

The field of view under 40x would be 0.38 mm. You will be looking at very small organisms, so it might be helpful to think in terms of micrometers (μm) instead of millimeters (mm).

1 mm = 1000 μm

0.38 mm = 380 μm

4. Make a slide of the phytoplankton assemblage by placing a drop of water on the slide and covering it with the cover slip. Place under the lowest-powered objective on the microscope and focus. Can you see phytoplankton cells? Find two different phytoplankton cells and change to a higher magnification to see them in more detail, if necessary. The size of the cell can be estimated because you know the size of the field of view.

Sketch the two phytoplankton cells below and estimate their size.

Phytoplankton #1: Size

____

Phytoplankton #2: Size

____

5. Repeat this process using the second phytoplankton sample. This phytoplankton sample is a type of picophytoplankton. You will likely have to use your highest-power objective to see the picophytoplankton.

Picophytoplankton #1: Size

Picophytoplankton #2: Size

Discussion Questions:

1. How big is a period on this page compared to the large phytoplankton and the picophytoplankton?
2. What differences did you observe between the phytoplankton and the picophytoplankton?
3. What other things might you find in the ocean in these size ranges?
4. What benefits or drawbacks do you think there would be to studying phytoplankton that are so small?
5. The initial discovery of picophytoplankton was greatly facilitated by technologies used in the medical field. Discuss the possible reasons these technologies were first developed for the medical field.

NOTES:

Objective

The objectives of this activity are

1. to learn why scientists use molecular techniques to study picoeukaryotes
2. to investigate real DNA sequences from picoeukaryotes

Additional Materials

None

Background

This activity is based on two of the techniques discussed in the accompanying article, "Good things come in small packages." As a quick review:

- Denaturing Gradient Gel Electrophoresis (DGGE)—A technique used to separate different types of picoeukaryotes. It is based on the sequence of DNA. Sequences that are different will denature (break down) at different points on the gel, thus, each band that forms in a lane has a different DNA sequence and is a different type of picoeukaryote.
- DNA Probe for FISH—A strand of DNA with a specific sequence that will attach to any cell with a complementary sequence in your sample. This will make every picoeukaryote with that sequence glow under a microscope so you can count them.

Questions

1. Imagine that you are an oceanographer and have sampled water from off the coast of Hawaii. You separate out the smallest eukaryotic phytoplankton (picoeukaryotes) and look at them under the microscope. You take the photos shown in Figure 1. How many different types of picoeukaryote were there in this sample? (Hints: Are you sure there is only one type of picoeukaryote per photo? Are you sure that every photo is a different picoeukaryote? Is it even possible to tell?) Explain.

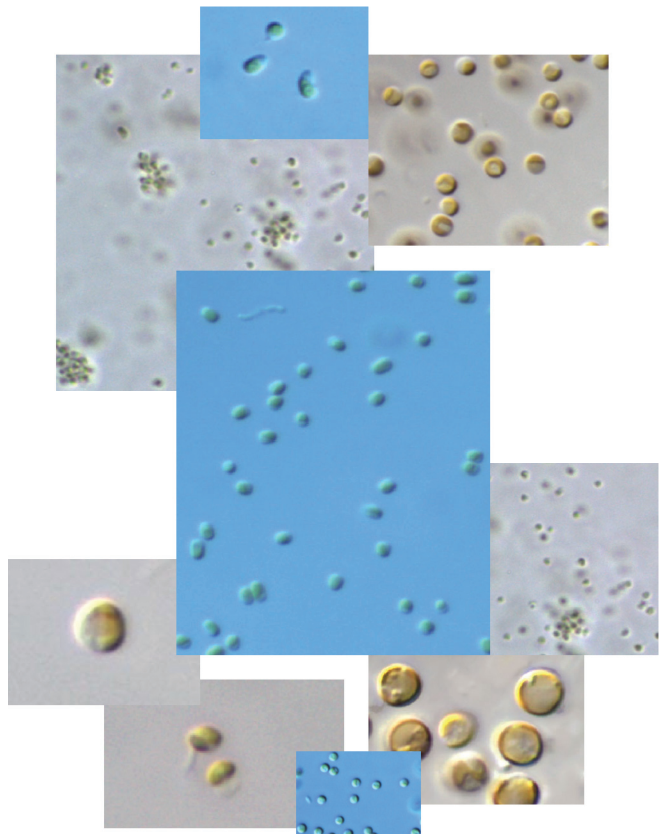


Figure 1: Picoeukaryotes (Pictures courtesy of Provasoli-Guillard National Center for Culture of Marine Phytoplankton—Bigelow Laboratory for Ocean Sciences)

2. To determine how many types of picoeukaryotes are in the water, you decide to run a DGGE (Figure 2). You have sampled from five different depths at this station; the surface of the ocean, 50 m deep, 100 m, 150 m, and 200 m. Based on this gel, what is the total number of different types of picoeukaryotes found at this station? Explain.

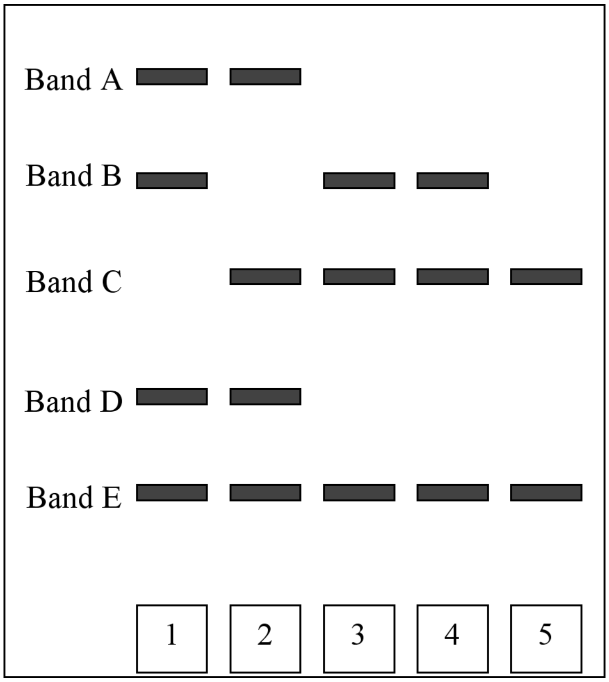


Figure 2: DGGE gel showing the diversity of picoeukaryotes at five different depths. Lane 1: surface, lane 2: 50 m, lane 3: 100 m, lane 4: 150 m, and lane 5: 200 m.

3. According to Figure 2, what can you conclude about the distribution of picoeukaryotes at this station as you move deeper into the ocean?

4. In order to learn more, you decide to sequence the bands so you can compare their DNA (Table 1). You are particularly interested in knowing if *Ostreococcus* sp. is present at this station—it is the smallest known picoeukaryote and the focus of your research. So, you also acquire the DNA sequence for *Ostreococcus* sp. for comparison. This is available from the National Center for Biotechnology Information, http://www.ncbi.nlm.nih.gov/. Just type *Ostreococcus* in the search box once you are on the Web site. Is it possible that *Ostreococcus* sp. is present at your station? Which bands do you think are most closely related to *Ostreococcus* sp.? Which are more distantly related? Explain.

5. What can you propose about the distribution of *Ostreococcus* sp. at this station?

6. If you were to design a DNA probe able to locate all of these types of picoeukaryotes, which section of DNA would be most useful? Explain.

7. If you were to design a probe to identify just those related to *Ostreococcus* sp., which section of DNA would be most useful? Explain

TABLE 1 Comparison of picoeukaryote DNA sequences	
Ostreococcus sp.	TCAGCCTGCTAAATAGTT---GGACCCTACTCTTAGGGCCACA-ACTTCT bases 1-50
Band A	TCAGCCTGCTAAATAGTT---GTACACTACTCTTAGTGCAGCA-ACTTCT
Band B	CCCGCCTGCTAAATAGGTGCGGGAATGCGCTTGCATTGCTGCA-ACTTCT
Band C	TCAGCCTGCTAAATAGTT---GGACCCTACTCTTAGGGCCACA-ACTTCT
Band D	CCCGCCTGCTAAATAGCTGTGGGAATGCGCTTGCATTGCCTCA-ACTTCT
Band E	CCCGCCTGCTAAATAGTACTGGGAATGC-TTAGCATTGCCAGAGACTTCT
Ostreococcus sp.	TAGAGGGACTATGTGCGTGTAGCACGTGGAAGTTTGAGGCAATAACAGGT bases 51-100
Band A	TAGAGGGACTATGTGCGTTTAGCACATGGAAGTTTGAGGCAATAACAGGT
Band B	TAGAGGGACTTTCGGTGACTAACCGAAGGAAGCTGGGGGCAATAACAGGT
Band C	TAGAGGGACTATGTGCGTGTAGCACGTGGAAGTTTGAGGCAATAACAGGT
Band D	TAGAGGGACTTTCGGTGACTAACCGAAGGAAGCTGGGGGCAATAACAGGT
Band E	TAGAGGGACTTTCGGCGCTAGGCCGAAGGAAGTTGGGGGCAATAACAGGT
Ostreococcus sp.	
Band A	CTGTGATGCCCTTAGATGTTCTGGGCCGCACGCGCGCTACACTGACGAAT
Band B	CTGTGATGCCCTTAGATGTCCTGGGCCGCACGCGCGCTACACTGGCACAC
Band C	CTGTGATGCCCTTAGATGTTCTGGGCCGCACGCGCGCTACACTGACGAAT
Band D	CTGTGATGCCCTTAGATGTCCTGGGCCGCACGCGCGCTACACTGGCACAC
Band E	CTGTGATGCCCTTAGATGTCCTGGGCCGCACGCGCGCTACACTGATGCGT
Table 1: DNA sequences from *Ostreococcus* sp. and five bands from the DGGE. The stars (*) indicate regions where all six sequences are the same and the dashes (-) indicate areas where gaps were necessary to align the sequences.	

NOTES:

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We all know about the larger animals in the ocean—fish, marine mammals, octopus, squid, and jellyfish. Like terrestrial animals, these ocean dwellers have to get their food from plants or the smaller animals that eat plants. What are all these plants and smaller animals? And how do they fit into the food chains and food webs that link the plants, the animals (herbivores) that eat them, and the animals (predators) that eat other animals (prey)?

What types of organisms are found in the ocean?

Before we learn about the food chains and food webs of the oceans, let's learn a little bit about the organisms found in them. One way that organisms in the ocean are classified is based on where they live and how they move around. Benthos includes organisms that live on or near the bottom of the ocean and includes seaweeds, certain fish, starfish, sea urchins, sea worms, and corals. Nekton includes animals that freely swim and can migrate for many hundreds of miles in the ocean, such as fish, marine mammals, and squid. Plankton includes organisms that move around in the ocean by tides and ocean currents, such as bacteria, single celled algae, jellyfish, and copepods.

There are many different types of plankton. One way we distinguish between the different types is based on how they get their food. Phytoplankton are single-celled algae that produce their own food by photosynthesis. They occur over a wide range of sizes, from photosynthetic bacteria (cyanobacteria) to large diatom chains and dinoflagellates. These larger phytoplankton are visible as small dots to the naked eye. Zooplankton are heterotrophic animals that feed on phytoplankton and other types of plankton. They range in size from protozoans like Paramecium, seen under the microscope in introductory biology classes, to the large Portuguese Man-of-War seen on the beach.

Another way plankton are grouped is based on their size (Figure 1). The smallest plankton are viruses, which were discovered in the 1980s [1]. Viruses live by stealth: they enter host cells and take over the host cell to make more viruses. Most known marine viruses live in bacteria, although some marine viruses attack phyto- and zooplankton. The next smallest size of plankton is dominated by bacteria. In the 1970s, marine biologists discovered how abundant very small bacteria were in the ocean because of new microscopic techniques [2]. Bacteria obtain their food by absorbing organic molecules or by using the Sun's energy to photosynthesize. The next larger plankton are mostly single-celled protozoans and photosynthetic algae, but also include some larval stages of multicellular organisms. Larger multicellular plankton include almost every known animal group either as larval stages of benthic adults (barnacle larvae, for example) or as animals that live their whole life in the plankton, such as copepods. Multicellular plankton can be microscopic, such as copepods and larvae which are no larger than a grain of rice, or they can be much larger and easily observed, such as jellyfish.

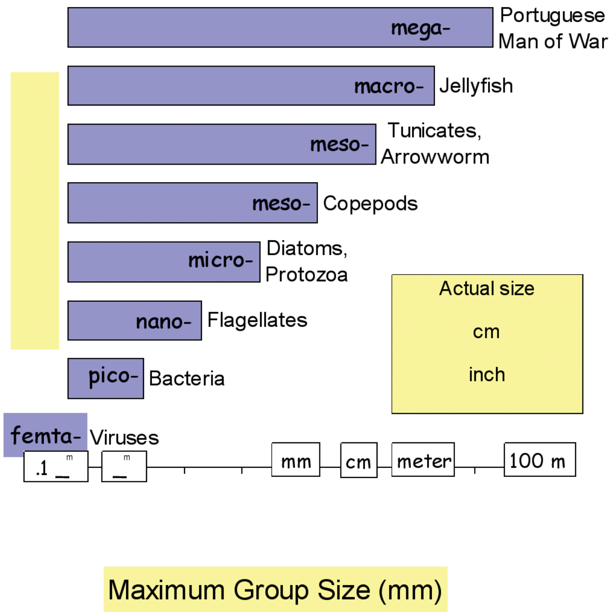

Figure 1. Plankton size classes displayed on a logarithmic scale from .0001 mm to 1000 mm (1 m). Bars show the maximum size for each plankton group. Note that the mesoplankton are represented with two size bars, reflecting a size range that spans two orders of magnitude, from 0.2 to 20 mm. Adapted from Sieburth et al. (1978) [3].

Where do the plankton live in the sea?

Plankton are not found in every part of the ocean. Phytoplankton, like trees and grass, require sunlight for photosynthesis; thus you would expect to find them where there is a lot of light in the water. As you might imagine, there is a lot of light in the surface waters of the ocean. In deeper coastal waters, however, sunlight does not reach the bottom, because it is absorbed and scattered by water molecules and particles. The surface layer of water, where there is enough light for photosynthesis, is called the photic zone. This is where the phytoplankton must live to get enough light to photosynthesize their food. In fact, there is so much light in the photic zone that, worldwide, photosynthesis by phytoplankton is as much as photosynthesis by land plants [4]!

Because zooplankton feed on phytoplankton, you would expect to find them where the phytoplankton are most abundant; and that is true. The zooplankton must spend a lot of their time in the photic zone so they can eat the phytoplankton, however, when they are in these brightly lit waters, they run the risk of being seen by their predators. So how do they escape predation?

How do zooplankton escape predators?

The transparent sunlit waters found at the surface of the ocean offer no place for prey to hide from their predators. So, instead of hiding behind a tree, or under a rock, they have other mechanisms for avoiding detection by their predators. The most obvious adaptation is that plankton are small and transparent, which greatly reduces their visibility in surface waters [5]. In addition, because they have high rates of reproduction, individuals are quickly replaced. Populations of single-celled organisms grow rapidly by individuals dividing in two. Populations of multicellular organisms may also grow rapidly by asexual reproduction (for example, cladocerans and tunicates). Although individuals may be eaten, these populations may “escape” predation by producing more new individuals than the number that are eaten.

Slower growing, sexually reproducing zooplankton can avoid predation by vertical migration between the sunlit surface and deeper, darker waters. Many copepod species perform diel vertical migration, which means that they eat phytoplankton in surface waters during the night, but sink or swim to deeper water during the day to avoid visual predators such as fish. However, reverse vertical migration was observed in Puget Sound: copepods migrated to the surface during the day and to deeper waters at night. This reversal appeared to be caused by invertebrate predators such as chaetognaths doing “normal” vertical migration, migrating to the surface at night and to deeper waters at night [6]. Diel vertical migration appears to be a flexible behavior that is influenced by the presence or absence of fish and invertebrate predators, but may also be influenced by feeding habits and reproductive habits. A food web includes all of these interactions—zooplankton eating phytoplankton, invertebrate predators eating zooplankton, and fish predators eating zooplankton.

Food chains and food webs

Scientists once believed that ocean ecosystems were characterized by very simple food chains. In a food chain, the phytoplankton are eaten by copepods, which are eaten by sardines and anchovies, which are eaten by striped bass and blue fish, which are eaten by tuna and sharks. This linear arrangement of predation was the classical picture of ocean food chains until the 1970s. Then, marine biologists began to discover that most photosynthesis and respiration in the ocean was by microorganisms less than 20 micrometers (μm) in size, rather than larger phytoplankton and animals [7]. These microorganisms compose the microbial loop, which includes bacteria, viruses, protozoa, and small phytoplankton [8]. The simple food chain which progresses from one trophic level to another has been replaced by a more complex food web, which includes the microbial loop (Figure 2).

Bacteria are usually thought of as decomposers, but in marine food webs they are a key player in the microbial loop where their food is a soup of dissolved organic matter (DOM). This DOM soup comes from several sources [8]. Phytoplankton release DOM to the ocean around them. Copepods produce DOM when they eat phytoplankton cells; sometimes they break open the phytoplankton and DOM spills out into the ocean from this "sloppy" feeding. Finally, viruses may cause DOM to spill out of their hosts. Much of the DOM is too large for bacteria to eat, so bacteria release enzymes into the ocean to break apart (digest) the larger DOM into smaller pieces.

So far in the microbial loop, DOM has moved from phytoplankton, zooplankton, and viruses to bacteria (Figure 2). What eats the bacteria? Bacteria are eaten by protozoa: flagellates such as *Euglena* and ciliates such as *Paramecium*. Bacteria are also eaten by larger zooplankton called tunicates, which are primitive chordates [9]. Some tunicates filter feed by pumping water into their bodies, collecting particles that become attached to a sticky "style" which is digested [9]. Copepods, however, cannot eat bacteria because these cells are too small; instead, copepods eat ciliates and flagellates, which eat bacteria [10]. In this way, the microbial loop connects back to the food chain: copepods eat protozoa which eat bacteria which eat DOM from phytoplankton. Instead of transferring organic matter from phytoplankton to copepods directly, there is a loop in this food web.

Marine biologists also have new ideas about predators. Besides fish predators, there are invertebrate predators: jellyfish, ctenophores (comb jellies), and chaetognaths (arrow worms) [11]. In addition to copepods, these predators eat a wide variety of prey: larvae of benthic invertebrates, fish larvae, protozoan flagellates and ciliates, and even other planktonic predators [11]! Examples of some of these organisms can be seen in Figure 2 and Figure 3.

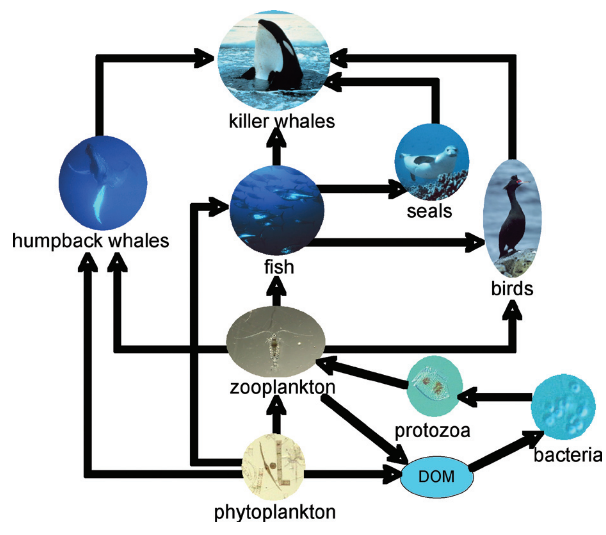

Figure 2. Marine food web with the classical food chain of phytoplankton, zooplankton, fish, and whales. Note thathumpback whales are baleen whales, which strain plankton through their baleen. Seals and birds breathe air as do whales. The microbial loop [dissolved organic matter (DOM), bacteria, and protozoa] is the most recently discovered part of the marine food web. (Photographs are courtesy of the National Oceanic and Atmospheric Administration/Department of Commerce and the Bigelow Laboratory for Ocean Sciences.)

How do planktonic food webs affect you?

Marine food webs play a significant role in global warming caused by humans burning fossil fuels which increases the carbon dioxide in the atmosphere. Marine food webs decrease atmospheric carbon dioxide through a "biological pump," which moves carbon from surface waters to the bottom of the ocean. The pump starts with phytoplankton taking up carbon dioxide during photosynthesis [4]. Phytoplankton growth causes more carbon dioxide to enter the ocean from the atmosphere. The carbon in phytoplankton enters the marine food web (Figure 2) and is removed from surface waters to the deep ocean, where it will stay many years before it is returned to the atmosphere.

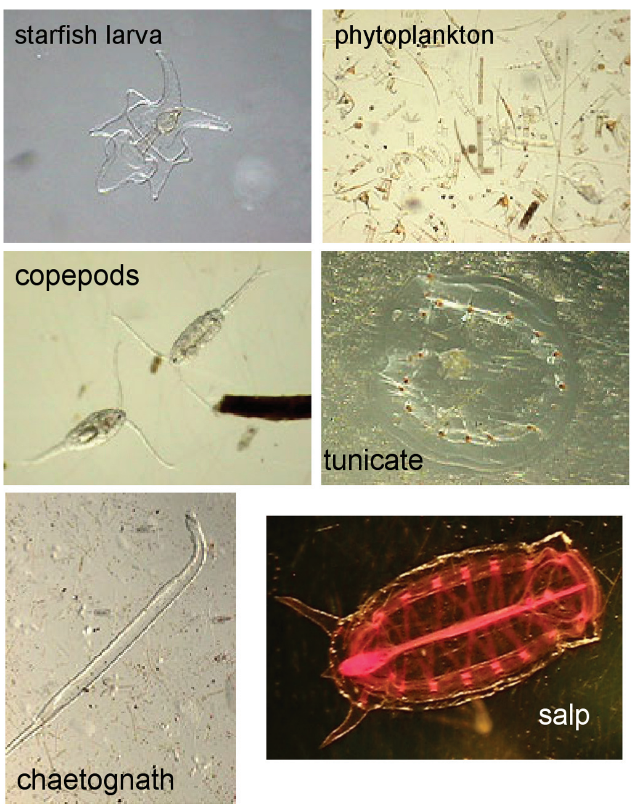

Figure 3. Examples of some of the planktonic organisms mentioned in this article. The salp has been colored with a purple stain to make it more visible. (Photograph of salp by Dr. J.W. Ambler; other photographs courtesy of the Bigelow Laboratory for Ocean Sciences.)

How does carbon dioxide get removed from surface waters?

When zooplankton migrate to greater depths, they may be eaten and not return to the surface. In addition, carbon moves downward with the sinking of fecal pellets and dead calcium carbonate shells of small marine animals. The ocean removes approximately half of all the carbon dioxide that humans put into the atmosphere from fossil fuels and clearing forests [12]. Without the biological pump, there would be twice as much carbon dioxide from humans in the atmosphere and probably faster global warming.

How do marine biologists study oceanic food webs?

Marine biologists have been studying food webs for a long time. Many study the interactions between predator and prey, or between an herbivore and phytoplankton. Putting the whole picture together is a daunting task. Marine biologists are like detectives and use as many types of evidence as possible: feeding experiments, long term-sampling programs, satellites, and computer models. They anchor buoys in coastal waters to collect temperature and current data over long periods of time. Satellites continuously record sea surface temperature and ocean color, which is used to measure phytoplankton abundance [13]. These continuous records of the environment show effects of storms and seasonal patterns. Biologists collect plankton samples to see how they are affected by the physical environment and food web interactions. Our project off the coast of Wallops Island, Virginia, combines all these approaches to understand food web interactions in the coastal ocean.

Acknowledgments

Acknowledgements for Title Page Photo: Background photo by Dr. N.M. Butler; inserted photos courtesy of the Bigelow Laboratory for Ocean Sciences.

Additional Reading

W.S. Johnson and D.M. Allen, *Zooplankton of the Atlantic and Gulf Coasts, A Guide to Their Identification and Ecology, Baltimore,* The Johns Hopkins University Press, 2005.

C.M. Lalli and T.R. Parsons, *Biological Oceanography, An Introduction,* 2nd ed., Oxford: Butterworth Heinemann, 1997.

C.B. Miller, *Biological Oceanography,* Oxford: Blackwell Publishing, 2004.

J.W. Nybakken, *Marine Biology, An Ecological Approach,* 5th ed., San Francisco: Addison Wesley Longman, Inc., 2001.

J.L. Sumich, *An Introduction to the Biology of Marine Life,* 7th ed., Boston: WCB McGraw-Hill, 1999.

C.D. Todd, M.S. Laverack, and G.A. Boxshall, *Coastal Marine Zooplankton, a Practical Manual for Students,* 2nd ed., Cambridge: Cambridge University Press, 2003.

Web Sites

http://faculty.washington.edu/cemills/

Dr. Claudia E. Mills is a research scientist at the University of Washington who works on the gelatinous zooplankton, especially jellyfishes and ctenophores. Her Web page contains a wealth of information on a wide variety of jellies and includes links to Web pages of other scientists working on jellies.

http://www.uwm.edu/People/jrs

Dr. Rudi Strickler is a faculty member at the University of Wisconsin–Milwaukee who specializes in filming the behavior of zooplankton. His Web page contains information on the biology and behavior of copepods and cladocerans and includes a large number of fascinating, and often amusing, video clips.

http://jaffeweb.ucsd.edu/pages/celeste/copepods.html

The Virtual Copepod Page is the result of a collaboration between three plankton biologists: Celeste Fowler at Scripps Institute of Oceanography, Dr. Jeannette Yen at Georgia Institute of Technology, and Dr. Jules Jaffe at the Scripps Institution of Oceanography. Their Web page presents a variety of still images, animations, and movies depicting the behavior of copepods, and also provides links to other copepod Web pages.

http://www.bigelow.org/education.html

The Bigelow Laboratory for Ocean Sciences offers a wide variety of activities, information, and resources for students and teachers wishing to learn more about food webs and processes in the oceans.

http://www.biosci.ohiou.edu/faculty/currie/ocean/

Dr. Warren J.S. Currie is a faculty member at Ohio University. His Web page, “The Plankton Net,” offers a diversity of resources pertaining to plankton ecology, marine biology, and biological oceanography, including instructions on how to make your own plankton net!

References

[1] J. Fuhrman and C.A. Suttle, “Viruses in marine planktonic systems,” *Oceanography,* vol. 6, pp. 52–63, 1993.

[2] F. Azam, T. Fenchel, J.G. Field, J.S. Gray, L.A. Meyer-Reil, and F. Thingstad, "The ecological role of water-column microbes in the sea," *Marine Ecology Progress Series,* vol. 10, pp. 257–263, 1983.[3] J.McN. Sieburth, V. Smatecek, and J. Lenz, "Pelagic ecosystem structure: heterotrophic compartments of the plankton and their relationship to plankton size fractions," *Limnology and Oceanography,* vol. 23, pp. 1256–1263, 1978.

[3] J.M. Sieburth, V. Smatecek, and J. Lenz, "Pelagic ecosystem structure: heterotrophic compartments of the plankton and their relationship to plankton size fractions," Limnology and Oceanography, vol. 23, pp. 1256–1263, 1978.

[4] P.G. Falkowski, "The ocean's invisible forest," *Scientific American,* vol. 287, pp. 54–61, August 2002.

[5] S. Johnsen, "Transparent animals," *Scientific American,* vol. 260, pp. 63–71, February 2000.

[6] M.D. Ohman, B.W. Frost and E.B. Cohen, "Reverse diel vertical migration: an escape from invertebrate predation," *Science,* vol. 220, pp. 1404–1407, June 24, 1983.

[7] L.R. Pomeroy, "The ocean's food web, a changing paradigm," *BioScience,* vol. 24, pp. 499–503, September 1974.

[8] F. Azam, "Microbial control of oceanic carbon flux: the plot thickens," *Science,* vol. 280, pp. 694–696, 1 May 1998.

[9] A.L. Alldredge and L.P. Madin, "Pelagic tunicates: unique herbivores in the marine plankton," *BioScience,* vol. 32, pp. 655–663, September 1982.

[10] U. Sommer and H. Stibor, "Copepods—cladocera—tunicate: the role of three major mesozooplankton groups in pelagic food webs," *Ecological Research,* vol. 17, pp. 161–174, 2002.

[11] J.E. Purcell, "Effects of predation by the scyphomedusan Chrysaora quinquecirrha on zooplankton populations in Chesapeake Bay, *Marine Ecology Program Series,* vol. 87, pp. 65–76, 1992.

[12] G.C. Hegerl and N.L. Bindoff, "Warming the world's oceans," *Science,* vol. 309, pp. 254–255, July 8, 2005.

[13] C.R. McClain, M.L. Cleave, G.C. Feldman, W.W. Gregg, S.B. Hooker, and N. Kuring, "Science quality SeaWIFS data for global biosphere research," *Sea Technology,* September 1998.

Julie W. Ambler is a professor in the Department of Biology at Millersville University in Millersville, PA, where she teaches ecology and directs undergraduate research. She also teaches biological oceanography at the Marine Science Consortium at Wallops Island, VA. Dr. Ambler received her Ph.D. from the Department of Oceanography at Texas A&M University, where she studied how different types of plankton affected copepod egg production in Galveston Bay. She has also studied deep sea animals off the Oregon coast; vertical migration of copepods from the Pacific Ocean; copepod swarms in mangrove prop roots in Belize, Central America; and models of planktonic food webs for coastal waters off the southeastern U.S. Currently, Dr. Ambler is working with Dr. Butler to study zooplankton from coastal waters off Chincoteague, VA, in a collaborative project with the NASA Goddard Space Flight Center.

Nancy M. Butler is a professor in the Department of Biology at Kutztown University in Kutztown, PA, where she teaches environmental studies, limnology, and zoology, and directs undergraduate research. She also teaches Ecology of Marine Plankton at the Marine Science Consortium at Wallops Island, VA. Dr. Butler received her Ph.D. from the Department of Zoology at the University of British Columbia, where she studied the feeding behavior and ecology of copepods. She has studied plankton communities in ecosystems as diverse as high alpine lakes, the Great Lakes, and coral reefs. Current research projects include studies of the swarming behavior of plankton, with emphasis on coral reef mysid populations. In addition, she is working with Dr. Ambler on a collaborative project with the NASA Goddard Space Flight Center studying zooplankton communities in the coastal waters off Chincoteague, VA.

Lab Exercises and Activities for Oceanography

References and Links

1. NASA Phytoplankton Web links

   http://www.bigelow.org/foodweb/microbe5.html

   http://phytoplankton.gsfc.nasa.gov/

2. Build a Plankton Net

   http://www.bigelow.org/foodweb/satellite2.html

3. NASA Chain or Web? Web links

   http://www.bigelow.org/foodweb/chain0.html

4. NASA Algal Blooms Web links

   http://www.bigelow.org/foodweb/bloom0.html

5. Visit to an Ocean Planet: Building a Plankton Net, Plankton Identification

   http://topex-www.jpl.nasa.gov/education/activities/ts3meac3.pdf

6. SeaWiFS Activities from the Teacher's Guide

   http://oceancolor.gsfc.nasa.gov/SeaWiFS/TEACHERS/

7. NOAA's Undersea Research Program (NURP)

   http://www.nurp.noaa.gov/Spotlight/ContObserv.htm

8. EPA Mid-Atlantic Integrated Assessment (MAIA) New Indicators of Coastal Ecosystem Condition

   http://www.epa.gov/maia/html/indicators.html

9. Bigelow Laboratory for Ocean Sciences

http://www.bigelow.org/education.html

10. Flow-cam Instrument for continuously monitoring and imaging phytoplankton

    http://www.bigelow.org/flowcam/flo_e2.html

11. Foundations of Phytoplankton

    http://phytoplankton.gsfc.nasa.gov/

Glossary

Asexual reproduction—reproduction of new individuals occurs by a single cell splitting in two or by a multicellular organism budding new individuals. Any reproduction that does not involve the joining of egg and sperm.

Buoys—floating objects that are anchored to the bottom, usually used to mark entrances to harbors or positions of crab pots. Scientists use buoys to collect data.

Chordates—animals that have, at some stage of development, a primitive backbone, dorsal nerve chord, gill slits, and tail. Humans and all other vertebrates are chordates.

Copepods—small crustaceans that resemble shrimp, sometimes called the "insects of the sea" because they are so numerous.

Diel—24 hour period that includes day and night.

Dissolved organic matter (DOM)—complex organic molecules such as carbohydrates, proteins and fats.

Fecal pellets—feces of zooplankton which are produced in compact oblong cases.

Heterotrophic—eating other organisms to gain food.

Organic molecules—molecules that contain carbon and hydrogen, and often other atoms such as oxygen, nitrogen, phosphorus, and sulfur.

Photosynthetic —using the Sun's energy to produce food.

Trophic level—levels of a food chain such that each higher trophic level is further away from the primary producers, which are in the first trophic level.

The science in this section may be a bit advanced for the high school classroom. As this will not be the case for all high school classrooms, we deemed it best if we included a special "Advanced Section" for those wishing to extend their oceanographic studies through additional activities and science articles.

NOTES:

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Hydrospheric & Biospheric Sciences Laboratory

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Carbon is the basic building block of life. Through the process of photosynthesis, plants on land, or algae living in lakes and oceans, take up carbon dioxide (CO_2) and convert this gaseous form of carbon into living organic products (such as carbohydrates, proteins, fats, etc.). Through the process of respiration, organisms break down these organic compounds for energy, metabolizing them into various forms of chemical compounds and regenerating the CO_2.

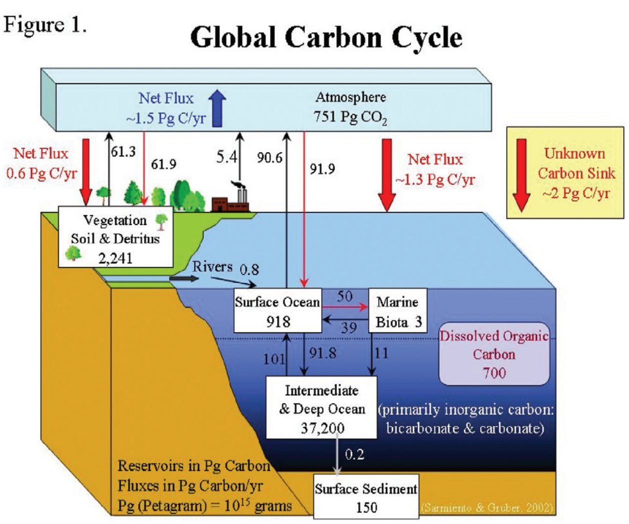

Figure 1: The global carbon cycle (values from the 1990s shown and schematic developed from [5] (Sabine et al. 2004), and [6] (Field et al. 2006). The figure does not show the vast amount of carbon that resides within rocks and deep ocean sediments. The values inside the reservoir boxes (for example, vegetation or atmosphere) represent the amount of carbon within the reservoir. The values next to the arrows represent the fluxes (or flow) of carbon from one reservoir to another. The wide red and blue arrows denote the net flux of carbon from the atmosphere (red) and to the atmosphere (blue). Values in parentheses represent the percentage of carbon derived from human activities. The biological processes of photosynthesis for the ocean is shown as a red arrow from DIC (dissolved inorganic carbon, primarily as bicarbonate and carbonate), to the sum of marine biota and DOC (dissolved organic carbon); respiration is the black arrow pointed towards DIC.

Carbon-derived materials such as oil, coal, and wood are important sources of energy and are materials that advance human civilization. Coal, natural gas, and petroleum are collectively called fossil fuels, because they are derived from the buried remains of plants, animals, and algae that are exposed to high heat and pressure over millions of years. The combustion (or burning) of fossil fuels (for electricity, heating, transportation, etc.) and wood (from forest fires and home heating) returns these stored organic materials to carbon dioxide. Thus, the carbon in fossil fuels that has been buried beneath Earth's surface for millions of years is being rapidly released into Earth's atmosphere as carbon dioxide. Current levels of carbon dioxide in Earth's atmosphere (380 parts per million—ppm; [1]) are much higher than at any time in the past 650,000 years for which we have scientific data (<300 ppm; [2]), and have increased significantly since the industrial revolution of the 1750s (from 280 ppm; [3]).

The level of carbon dioxide in the atmosphere plays an important role in earth's climate through the "greenhouse effect." Carbon dioxide in Earth's atmosphere is considered a greenhouse gas because it is transparent to much of the Sun's radiation, but blocks long-wave infrared radiation (primarily as heat) re-emitted by Earth rather than allowing the heat to escape into space. As levels of carbon dioxide increase in earth's atmosphere, more heat is trapped, resulting in higher temperatures on a global scale. These temperatures are only slightly higher than usual, but promote longer growing seasons, redistribution of vegetation, melting of glaciers, sea-level rise, and other environmental impacts.

As a result, understanding the global carbon cycle provides insight about life on Earth, as well as its role in climate change. The impact of global industrialization over the past few centuries to Earth's carbon cycle is the subject of much scientific research. A significant amount of carbon is released every year from the burning of fossil fuels [4]. Of the carbon released, ~50% remains in the atmosphere (resulting in higher CO_2 concentrations), ~28% is taken up by vegetation on land (includes CO_2 emissions from land due to deforestation and other land use changes), and ~26.6% dissolves into the ocean surface [5, 6]. The previous values exceed 100% because of uncertainties associated with carbon flux estimates. One of the current mysteries is the allocation of the 466 petagrams (Pg = 10^{15} grams) of CO_2 emissions generated from human activity since 1850 [6]. Current estimates suggest that the atmosphere retains 187 Pg of this CO_2, and the ocean contains 118 Pg [6]. The remainder, 161 Pg, is assumed to be stored on land as vegetation through re-growth of forests and in soils [5]. However, a portion of this carbon could also be stored in ocean waters or sediments. Solving the mystery of the “missing” (unaccounted) carbon is critical to understanding how increasing emissions of CO_2 impact the global carbon cycle and climate change.

Figure 2.

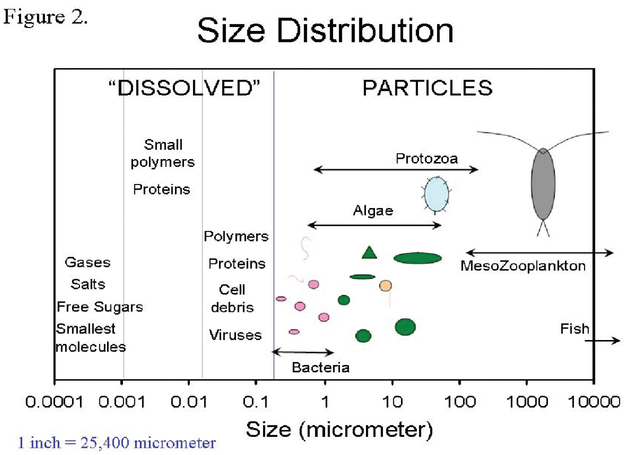

Figure 2: Schematic of the size distribution of dissolved materials and particles in the ocean.

Dissolved Organic Carbon

Carbon in the ocean is categorized as dissolved inorganic carbon (e.g., CO_2, bicarbonate, carbonate), particulate inorganic carbon (ex. calcium carbonate present in seashells), particulate organic carbon (POC; composed of living and dead organisms), and dissolved organic carbon (DOC). Particles and dissolved materials are operationally defined as matter larger or smaller than 0.2 μm, respectively (Figure 2). Approximate size ranges of marine biota and dissolved matter are given in Figure 2. Hence, DOC is defined as the organic carbon content in seawater which passes through a 0.2 μm pore-sized filter. It is primarily composed of small polymers of carbohydrates and proteins released into the water.

Although dissolved organic carbon represents <2% of the total carbon in the ocean, it comprises nearly all (>97%) of the organic carbon in the ocean [3]. Because DOC represents an important component of the global carbon cycle (equivalent in magnitude to carbon in atmospheric CO_2), investigating the sources and removal of DOC within the ocean is vital to understanding the carbon cycle. Photosynthesis is the principal source of DOC to aquatic ecosystems [7]. DOC is either released directly by phytoplankton as they grow or can be indirectly released as they are fed upon by small crustacean animals, from viral-induced breakage of phytoplankton or through break down of detritus (dead material) by microbial communities, primarily bacteria.

The potentially large fluxes of carbon in the coastal ocean underscore the significance of the coastal ocean to the global carbon cycle. The coastal ocean accounts for ~20% of the ocean’s photosynthesis [8]. Rivers transport ~0.3 Pg of DOC per year to the ocean (and 0.2 Pg POC per year) [5], yet the terrigenous contribution (land-derived carbon, primarily from vegetation and soils) to this overall flux is not well known [9]. Because terrestrial ecosystems are highly productive, their contributions to coastal ocean DOC could be significant. While particles from terrestrial ecosystems are primarily deposited in the coastal region [10], DOC is considered the main conduit for transporting terrestrial organic carbon into the deep ocean. An important research question is whether terrestrial carbon inputs to the ocean have increased over the past 150 years and account for some of the missing carbon.

Historically, coastal ocean waters have been a source of CO_2 to the atmosphere because of river contributions of dissolved inorganic carbon (DIC; currently 0.4 Pg per year) and land-derived organic carbon that is subsequently degraded to CO_2 by microbes in the coastal ocean [5]. However, human population growth, agriculture, and other activities along coastal regions have resulted in the export of higher levels of nutrients to the ocean, which support more extensive phytoplankton blooms in coastal waters. The enhanced photosynthesis in the surface ocean removes more CO_2 from seawater enhancing the solubility of atmospheric CO_2 into the ocean due to the reduced CO_2 concentration in the surface ocean with respect to the atmosphere. Burial of the organic carbon from phytoplankton blooms into coastal sediments would sequester this carbon from the atmosphere. Furthermore, recent evidence demonstrates the importance of CO_2 outgassing from rivers to the atmosphere (Figure 1) with tropical rivers of greatest significance due to microbial degradation of large inputs of land vegetation and soil derived organic matter into these rivers [5].

DOC can be converted to CO_2 when it is broken down by microbial communities or by sunlight. Microbial communities in the ocean are the primary recyclers of organic materials, accomplishing most of the decomposition of particles and DOC to CO_2. An increase in the conversion of the total DOC reservoir in the ocean to CO_2 of 1% annually would exceed the amount of CO_2 released from fossil fuel combustion [11]. Higher rates of conversion, due to increasing microbial respiration from higher ocean temperatures, or from increasing ultraviolet radiation to the ocean surface could have profound effects to atmospheric CO_2 levels and possibly to climate change. The potential impact of DOC on atmospheric CO_2 and climate change is rather minor compared to other factors that impact the concentration of atmospheric greenhouse gases such as CO_2 and methane. For example, vast reservoirs of methane trapped within frozen Arctic soils may be released as the soils thaw due to global warming. As the Arctic perma-frost warms, microbial respiration of organic matter within these soils could also release significant amounts of CO_2 to the atmosphere.

Chromophoric Dissolved Organic Matter

Chromophoric dissolved organic matter (CDOM) represents the colored fraction of DOC. CDOM is colored because it absorbs light at certain regions of the visible spectrum more intensely (violet and blue light). The wavelengths of light that are not absorbed can be scattered, and thus, the CDOM will be perceived as the color of the scattered light (from a faint yellow to brown). The substance that leaches from tea bags placed in water is an example of CDOM.

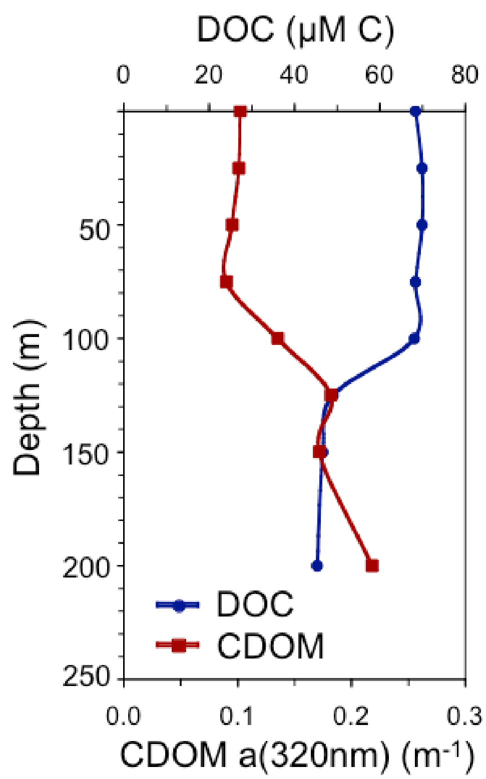

Figure 3: DOC and CDOM absorption distributions in the tropical North Atlantic Ocean. Higher DOC at the surface reflects biological production and release of DOC by phytoplankton, bacteria, and zooplankton. The lower CDOM values within the surface ocean layer compared to deeper waters demonstrate the impact of the photochemical oxidation by sunlight in surface ocean waters.

CDOM levels can vary both spatially and temporally. In coastal waters, CDOM can dominate the absorption of sunlight, particularly in the ultraviolet and blue regions of the light spectrum. Physical processes that promote vertical mixing of the coastal ocean such as winter seasonal mixing (due to storms) can introduce CDOM to the surface ocean. As sunlight intensity increases in spring and summer, the water at the ocean's surface warms making it less dense than water at depth, which is colder. This difference in density causes stratification between surface and deep ocean water, essentially forming a barrier that reduces the exchange of dissolved materials between the surface and deeper water. Sunlight can lead to the loss of CDOM and DOC in a process called photochemical oxidation, or photobleaching. A small portion of the absorbed sunlight can convert CDOM to CO_2 or cause a structural transformation of CDOM [12, 13, 14, 15]. Seasonal vertical stratification isolates DOM at depth from sunlight, resulting in DOC with greater color at depth than at the surface (Figure 3).

At regional and global scales, satellite observations combined with field observations have provided new insights into seasonal and interannual changes in photosynthesis on land and in the ocean [16, 17]. Satellite instruments used to study ocean color do not measure ocean constituents directly, but rather measure light leaving the ocean at multiple wavelengths (blue, green, red, etc.), which can be used to derive the concentration of ocean constituents, including not only chlorophyll, but also CDOM. Discharge of DOC from terrestrial sources and particles (detritus and minerals) into coastal waters by rivers and the presence of intense phytoplankton blooms in coastal waters complicate the optical properties of the coastal ocean. Thus, work focuses on trying to resolve and separate the optical signals of CDOM, chlorophyll (which represents algal biomass), and non-living particles in the coastal ocean and linking them to DOC concentrations in order to apply satellite observations to study coastal waters (Figures 4a and 4b). Measurements collected by satellites offers the capability to study the carbon cycle at much greater spatial and temporal scales than otherwise possible.

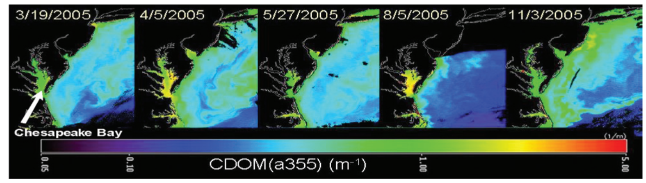

Figure 4a: Prototype satellite-derived CDOM absorption for the U.S. Mid-Atlantic coast from NASA's MODIS sensor on the Aqua satellite platform. Substantial changes in CDOM occur along the coastal ocean from spring to summer and summer to fall. CDOM absorption decreases from spring to summer, due to photochemical oxidation by sunlight. From summer to fall, storm events will vertically mix the water column and introduce CDOM from depth into surface waters.

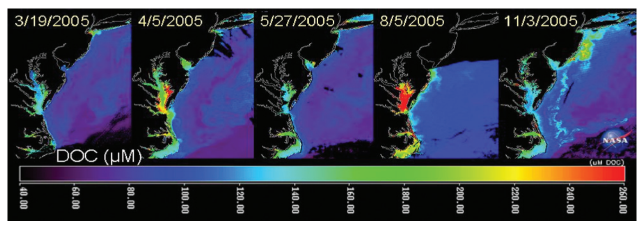

Figure 4b: Protoype DOC satellite image for the U.S. Mid-Atlantic coast from NASA's MODIS sensor on the Aqua satellite platform. The higher DOC concentrations along the coast are primarily due to land contributions of organic carbon to the ocean through rivers, bays and groundwater. The greatest seasonal change in DOC along the coastal ocean occurs from spring to summer. Much higher DOC concentrations are observed in summer compared to early spring due to direct and indirect release of DOC by marine organisms and accumulation of DOC resistant to bacterial degradation on the scale of weeks to months. A storm front that passed through the region on April 2 appears to have had a major impact on DOC between March 19 and April 5 from the influx of DOC from Chesapeake Bay into the nearby ocean.

Additional Reading

S.C. Doney. "The dangers of ocean acidification," *Scientific American,* 294(3): 58–65, March 2006.

D.A. Hansell and C.A. Carlson, "Marine dissolved organic matter and the carbon cycle," *Oceanography,* vol. 14, number 4, pp. 41–49, 2001. Can be accessed at:

http://www.tos.org/oceanography/issues/archive.html

L. Lippsett, "Earth can't soak up excess fossil fuel emissions indefinitely," *Oceanus,* vol. 44, 2005. Can be accessed at:

http://www.whoi.edu/oceanus/index.do

P.G. Falkowski, "Ocean's invisible forest," *Scientific American,* vol. 287, pp. 54–61, 2002.

Web Sites

http://www.usgcrp.gov/

The US Global Change Research Program Web site describes many ongoing scientific investigations of the Earth's changing climate. This Web site also includes recent news releases.

References

[1] C.D. Keeling and T.P. Whorf. "Atmospheric CO_2 records from sites in the SIO air sampling network." In *Trends: A Compendium of Data on Global Change.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A. Go to http://cdiac.ornl.gov/trends/co2/sio-keel for additional information.

[2] U. Siegenthaler, T.F. Stocker, E. Monnin, D. Lüthi, J. Schwander, B. Stauffer, D. Raynaud, J.-M. Barnola, H. Fischer, V. Masson-Delmotte, and J. Jouzel, "Stable carbon cycle-climate relationship during the late Pleistocene," *Science,* 310, pp. 1313–1317.

[3] A. Neftel, H. Friedli, E. Moor, H. Lötscher, H. Oeschger, U. Siegenthaler, and B. Stauffer. "Historical CO_2 record from the Siple Station ice core." In: *Trends: A Compendium of Data on Global Change.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A., 2005.

[4] J.L. Sarmiento and N. Gruber. "Sinks for anthropogenic carbon." *Physics Today,* 55(8), p. 30. http://www.physicstoday.org/pt/vol-55/iss-8/p30.html, 2002.

[5] C.L. Sabine, M. Heimann, P. Artaxo, D. Bakker, C.-T.A. Chen, C.B. Field, N. Gruber, C. LeQuéré, R.G. Prinn, J.E. Richey, P.R. Lankao, J. Sathaye, and R. Valentini, "Chapter 2: Current status and past trends of the global carbon cycle." In *SCOPE 62, The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World,* C.B. Field and M.R. Raupach (eds.), Island Press, Washington, D.C., pp. 17–44, 2004.

[6] C.B. Field, J. Sarmiento, and B. Hales, "Chapter 2: The carbon cycle of North America in a global context." In: *North American Carbon Budget and Implications for the Global Carbon Cycle (Prototype State of the Carbon Cycle Report (SOCCR)), Product 2.2.* http://www.usgscrp.gov/, 2006.

[7] U. Siegenthaler and J.L. Sarmiento, "Atmospheric carbon dioxide and the ocean," *Nature,* vol. 365, pp. 119–125, 1993.

[8] G.A. Knauer, 1993. "Productivity and new production of the oceanic systems." In R. Wollast, F.T. MacKenzie, and L. Chou (eds.), *Interactions of C, N, P and S Biogeochemical Cycles and Global Change.* Springer-Verlag, New York, pp. 211–231, 1993.

[9] J.L. Hedges, R.G. Keil, and R. Benner. "What happens to terrestrial organic matter in the oceans?" *Organic Geochemistry,* vol. 27, pp. 195–212, 1997.

[10] J.L. Hedges, "Global biogeochemical cycles: progress and problems," *Marine Chemistry,* vol. 39, pp. 67–93, 1992.

[11] J.L. Hedges, "Why dissolved organic matter?" In: D.A. Hansell and C.A. Carlson (eds), *Biogeochemistry of Marine Dissolved Organic Matter.* Academic Press, pp. 1–33, 2002.

[12] D.J. Kieber, X. Zhou, and K. Mopper, "Formation of carbonyl compounds from UV-induced photodegradation of humic substances in natural waters: Fate of riverine carbon in the sea." *Limnology and Oceanography,* vol. 35, pp. 1503–1515, 1990.

[13] N.V. Blough, "Photochemistry in the sea-surface microlayer," In: P.S. Liss and R.A. Duce (eds), *The Sea Surface and Global Change.* Cambridge University Press, pp. 383–424. 1997.

[14] R.F. Whitehead and S. De Mora. "Marine photochemistry and UV radiation," In: R.E. Hester and R.M. Harrison (eds), *Causes and Environmental Implications of Increased UV-B Radiation (Issues in Environmental Science and Technology No. 14).* The Royal Society of Chemistry, pp. 37–60, 2000.

[15] K. Mopper and D.J. Kieber, "Photochemistry and the cycling of carbon, sulfur, nitrogen, and phosphorus," In: D.A. Hansell and C.A. Carlson (eds), *Biogeochemistry of Marine Dissolved Organic Matter.* Academic Press, pp. 455–507, 2002.

[16] M.J. Behrenfeld and P.G. Falkowski, "Photosynthetic rates derived from satellite-based chlorophyll concentration." *Limnology and Oceanography,* vol. 42, pp. 1–20, 1997.

[17] M.J. Behrenfeld et al., "Biospheric primary production during an ENSO Transition." *Science,* vol. 291, pp. 2594–2597, 2001.

Discussion Questions

1. What problem does this article discuss?

2. Draw your own conclusions as to the solution(s) to this problem.

3. Design an experiment to support your solution(s).

4. What scientific laws may possibly be challenged as a result of the solution to this problem?

5. Why is it important to know the answer to this problem?

Glossary

Crustacean—any of a large class of mostly aquatic organisms that have an exoskeleton; examples lobsters, shrimps, crabs, wood lice, water fleas, and barnacles.

Detritus—dead material that is starting to disintegrate.

Inorganic—class of compounds not having a carbon basis; not from a living organism.

Microbial—caused by a microscopic organism, often bacteria.

Organic—class of compounds having a carbon basis; being or derived from a living organism.

Polymer—a naturally occurring or synthetic compound consisting of large molecules made up of a linked series of repeated simple units.

Terrigenous—produced on land.

Introduction

Carbon dioxide dissolves in the ocean. There is an exchange of carbon dioxide between the atmosphere and the ocean's surface.

Carbon dioxide dissolved in water (known as being in solution) is acidic.

Marine Carbon Cycle

"Carbon is produced in the upper ocean by photosynthesis, and it moves up the trophic levels (zooplankton, nekton). Most of the carbon in the upper ocean is recycled (the biologists can comment more on that), but some "drops out" and sinks. In the deep ocean, organic carbon is "remineralized" by bacterial respiration (which uses dissolved oxygen), converting it back to inorganic carbon and also producing dissolved nutrients. You can see in the carbon cycle diagram that there is much more inorganic carbon in deep waters than in the surface ocean. This means that deep ocean waters also have higher N and P concentrations than surface waters." (NASA SeaWiFS Project—http://seawifs.gsfc.nasa.gov).

What you need:

- Eye protection
- 2 beakers
- Universal Indicator solution (Universal indicator goes yellow in the presence of acid)
- Sea water
- Tap water (fresh water)
- Drinking straw
- Stopwatch
- A copy of the carbon cycle diagram (below)

Safety

Always wear eye protection. Blow gently through the straws; do NOT suck up water. Dispose of the straws at the end of the activity.

Procedure

1. Pour 100 mL of sea water into one beaker and 100 mL of fresh water into the other beaker.
2. Put 5 drops of universal indicator into each.
3. Using the straw, blow gently and consistently into the water, first for the sea water, then the fresh water. For each, record the time it takes the indicator to become yellow.

Questions

1. What did it mean when the indicator was yellow?
2. Which beaker turned yellow quickest?
3. Why did you have to blow through a straw in this experiment?
3. Which water absorbs more carbon dioxide before becoming acidic?
4. Highlight this part of the carbon cycle on your diagram below.

Extension Questions

1. Carbon is in the cycle in various forms. Where do we see these in daily life? Answers will vary.

2. Coal and natural gas form from ancient plants. What processes affected these plants that probably won't affect the plants you see outside the window?

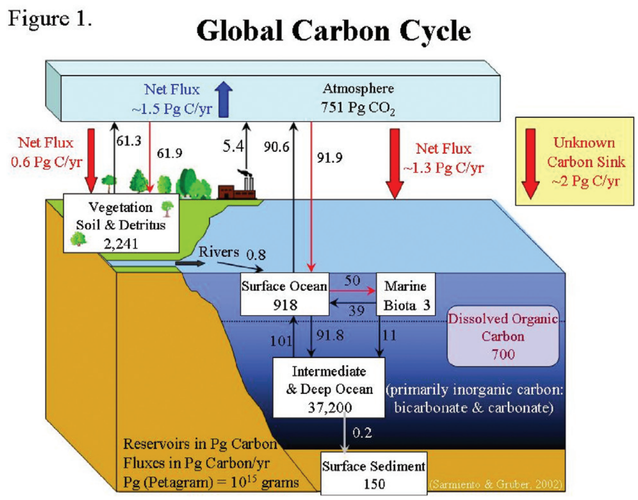

Figure 1. (From article).

Introduction

Chromophoric dissolved organic matter (CDOM) represents the colored fraction of dissolved organic carbon (DOC). CDOM is colored because it absorbs light at certain regions of the visible spectrum. The substance that leaches from tea bags placed in water is an example of CDOM. Sunlight can lead to the loss of CDOM and DOC in a process called photochemical oxidation, or photobleaching. Most of the sunlight absorbed by CDOM (95–98%) does not cause a chemical change. The remainder of the absorbed sunlight can convert CDOM to CO_2 or cause a structural transformation of CDOM.

CDOM and Coastal Waters

CDOM levels can vary both spatially and temporally. In coastal waters, CDOM can dominate the absorption of sunlight, particularly in the ultraviolet and blue regions of the spectrum. Physical processes that promote vertical mixing of the coastal ocean in both the Northern and Southern hemispheres, such as winter seasonal mixing (due to storms) can introduce CDOM to the surface ocean. As sunlight intensity increases in spring and summer, the water at the ocean's surface warms making it less dense than water at depth, which is colder. This difference in density causes stratification between surface and deep ocean water, essentially forming a barrier that reduces the exchange of dissolved materials between the surface and deeper water.

What you need

- Eye protection
- 3 clear coffee mugs
- 3 tea bags (1 each: black tea, green tea, and Chamomile [herbal])
- Graduated cylinder
- Warm Tap Water
- Spoon

Safety

Always wear eye protection. Make sure the water is not too hot. You do NOT need to boil the water.

Procedure

1. Fill half of each clear mug with warm tap water.
2. Put one of each tea bag in a separate mug of water and stir.
3. Watch for the color changes in the water and record findings for each of the teas.
4. Slowly add water in increments into each of the mugs and stir after each water addition until each mug is full.
5. Record color changes after each incremental water addition until each mug is full.

Questions

1. Why did we use different types of teas (black, green, herbal)?
2. When you added the tea bags to the warm water, what did the substance coming from the tea bags represent?
3. What happened when you added more and more water to the mugs?
4. What processes in nature does the addition of water to the mugs represent?

Extension Questions

1. What other natural Earth materials could we use to demonstrate the same processes as seen with the tea bags.

2. What effect does sunlight have on CDOM and DOC?

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Imagine standing on a boat in the Gulf of Mexico and looking down at the water. Instead of seeing blue as expected, it is oddly red (Figure 1). What could cause this? It may be a harmful algal bloom.

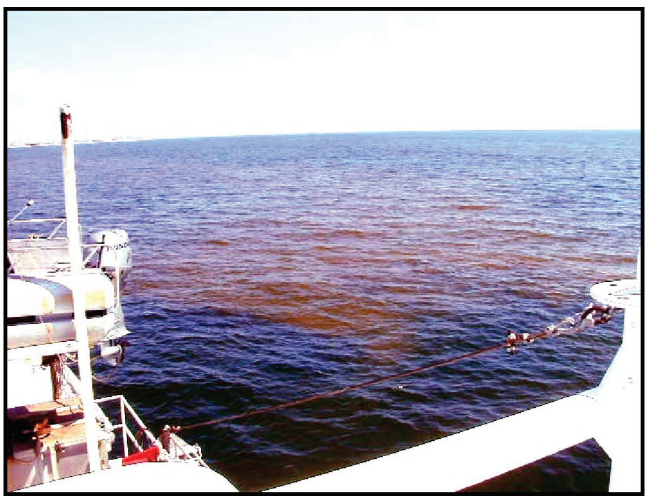


Figure 1. *Karenia brevis* bloom off Florida

Algae (also referred to as phytoplankton) are small, single celled organisms that grow in freshwater and oceans. When they grow rapidly, they can reach large numbers resulting in an algal bloom. Harmful algal blooms (HABs) are sometimes called red tides, but not all HABs discolor the water or turn it red. Sometimes, HABs are green, brown, or golden, depending on the algal species causing the bloom.

Harmful algae cause injury by producing toxins or disrupting aquatic food webs. HABs are not new, but they are getting more attention because of the increasing number of coastal residents. HABs are also being investigated by an increasing number of researchers from many fields. In the past, HABs were of concern primarily to taxonomists and shellfish growers; however, HABs are now studied by ecologists, oceanographers, molecular biologists, and remote sensing specialists, to name a few of the new disciplines that are now contributing to this field of study. Their efforts are being combined to try to predict and mitigate the effects of HABs.

From this increased attention, a number of new tools and techniques are being developed to detect HAB species and their toxins at low concentrations. Currently, scientists are developing monitoring techniques and models that emphasize remote sensing from buoys, autonomous underwater vehicles (unmanned free-moving craft; Figure 2), and satellites. Other new technologies, like molecular probes, are borrowed from medical science. These techniques help provide species identification when the HAB cells might be confused with other non-toxic cells. New toxin detection and quantification methods are also being developed to help provide early warning of harmful conditions in the oceans.

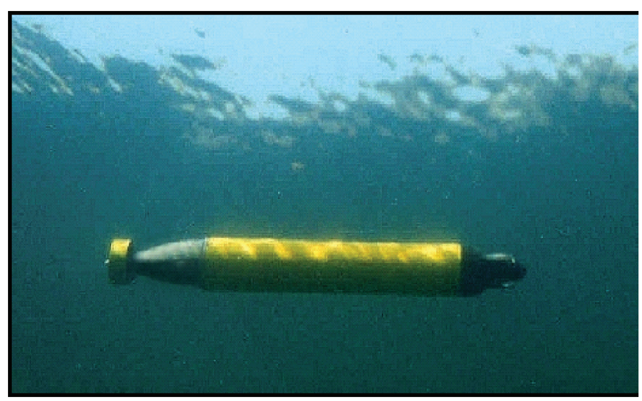


Figure 2. Autonomous underwater vehicles (AUVs) are used to monitor HABs.

There is a consensus in the field that HABs are happening more frequently and in places where they were not known to occur 10 or 20 years ago. Note that nearly every coastal area has reported HABs (Figure 3).

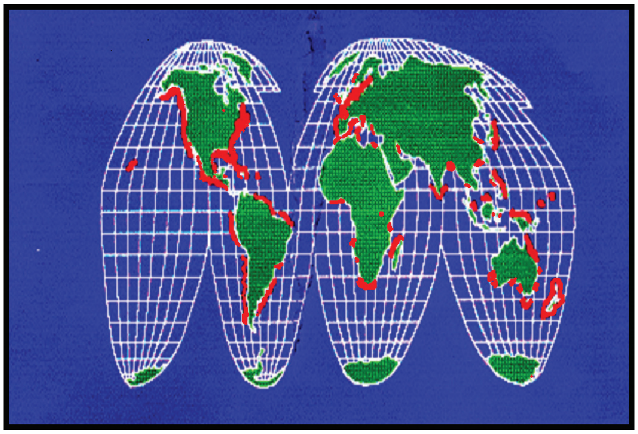


Figure 3. Reports of harmful algal blooms worldwide (in red).

Why Should We Care About HABs?

Effects of HABs include:

- Threat to human health
- Regional economic impacts
- Mass mortality of fish
- Loss of environmental quality
- Marine mammal deaths
- Effects on non-commercial species
- Water quality degradation

What is known about HABs and the toxins they produce?

HAB toxin production is a very active area of research because it affects human health, economics, and marine resources. The most significant public health problems caused by harmful algae are poisoning as a result of eating contaminated fish or shellfish. Here are a few examples of the types of poisoning that can occur from HAB toxin production.

Amnesic Shellfish Poisoning (ASP)

ASP was first recognized in 1987 on Prince Edward Island, Canada after locals consumed blue mussels. There were over 100 acute cases and 4 deaths. One of the organisms causing ASP is *Nitzschia pungens* f. multiseries, which produces the neurotoxin, domoic acid (Figure 4). A severe case of ASP includes symptoms of gastroenteritis, dizziness, headache, seizures, disorientation, short-term memory loss, and respiratory difficulty.

Figure 4. *Nitzschia pungens* f. *multiseries*, width ~3 µm (image by Rita Horner)

Ciguatera Fish Poisoning (CFP)

CFP was first recognized in the 1550s in the Caribbean, however, the causative organism was not identified until more recently. CFP has a pantropical distribution and is known from the Caribbean basin, Florida, the Hawaiian Islands, French Polynesia, and Australia. Higher trophic-level carnivores, such as fish, accumulate high levels of the toxin by feeding on herbivorous fish that feed on plants with an assemblage of benthic dinoflagellates including *Gambierdiscus toxicus,* which is responsible for ciguatoxin production (Figure 5). These fish may be toxic for up to two years after becoming contaminated. In extreme cases, death from respiratory paralysis may occur. There is no antidote for CFP, which is now considered a major health and economic problem in many tropical islands, for locals and for uninformed tourists.

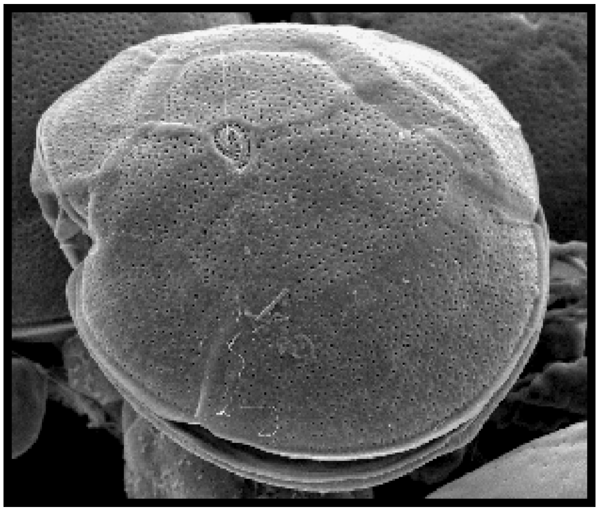


Figure 5. *Gamberdiscus toxicus*, size ~50 µm (image by Maria Faust)

Neurotoxic Shellfish Poisoning (NSP)

NSP is similar to CFP in that it also produces gastrointestinal and neurological symptoms. The dinoflagellate *Karenia brevis* is responsible for NSP (Figure 6). Blooms of *K. brevis* are marked by large patches of discolored water and massive fish kills. *Karenia brevis* is an unarmored dinoflagellate and can be ruptured easily by wave action, causing its toxins to become aerosolized and produce asthma-like symptoms. *K. brevis* blooms were first recognized in the 1880s. *K. brevis* blooms are known through much of the Gulf of Mexico and are most common off the western Florida continental shelf; however, in the fall and winter of 1987–88, there was a large *K. brevis* bloom in the coastal waters of North Carolina. The local economy lost $24 million dollars when many shellfish harvesting areas were closed for the entire season, during which 48 cases of NSP were reported.

Figure 6. *Karenia brevis*, size ~20 µm

Diarrhetic Shellfish Poisoning (DSP)

DSP was first reported in Japan in 1976. The causative organisms are several species of the dinoflagellate, *Dinophysis,* which produces okadaic acid (Figure 7). DSP produces symptoms that are often mistaken for a bacterial infection. DSP is not fatal and recovery is generally within three days, even without medical treatment. DSP has been reported in Spain, Chile, Thailand, Japan, and New Zealand. DSP has also been reported in northeast U.S. waters. Some consider DSP to be the most serious and globally widespread phycotoxin-caused seafood illness.

Figure 7. *Dinophysis* sp., size ~50 µm (image by Rita Horner)

Paralytic Shellfish Poisoning (PSP)

PSP was recognized by Native Americans before the arrival of European explorers. PSP is caused by saxitoxin, which was first characterized in 1957 and is recognized in 21 different forms. These saxitoxins contaminate shellfish. Food chain concentrations of saxitoxin in mackerel have resulted in marine mammal deaths. Saxitoxins act on the peripheral nervous system and the central nervous system through a sodium channel block, binding to receptor sites, and inhibiting nerve transmission to muscles. If contamination is severe enough, death may occur through respiratory failure. Other symptoms include gastrointestinal distress, tingling, numbness, and ataxia. These are symptoms common to most other algal toxin-related illness. Organisms containing saxitoxins include *Alexandrium catenella* and *Alexandrium tamarense* (Figure 8).

Figure 8. *Alexandrium* sp., size ~25 μm (Image by Rita Horner)

Cyanobacteria

Just as there are many saltwater species that cause HABs, there are freshwater species called blue-green algae (cyanobacteria) that cause similar problems. These can be recognized as green pond scum or algal mats. Common species are *Microcystis* and *Oscillatoria* (Figure 9). Characteristics of these freshwater HAB causing organisms are:

- Worldwide distribution in fresh water
- Sensitive to nutrient enrichment
- Cyanotoxins bioaccumulate in the food chain
- Produce neurotoxins and cause acute liver toxicity and gastrointestinal effects

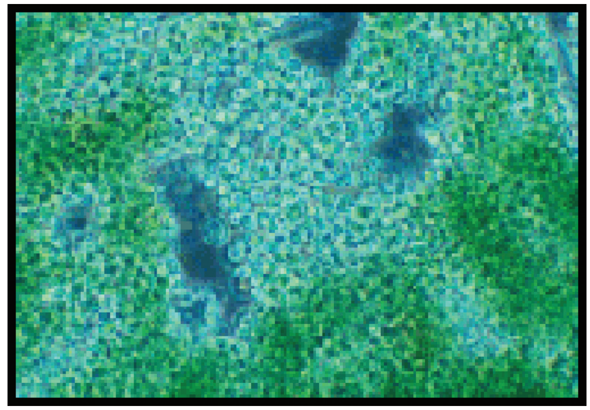


Figure 9. *Microcystis* sp., size ~2–3 μm (image by Hans Pearl)

Many questions are still unanswered regarding harmful algal blooms and the species that cause them; however, there are several actions that can be taken to reduce the effects of HABs. These actions include increased monitoring of environmental conditions, improving methods used to accurately identify the algal species that cause blooms, and ensuring safety of seafood by developing cost-effective methods for determining toxins in seafood.

Additional Reading

D.M. Anderson, "Red tides," *Scientific American,* vol. 271, pp. 62–68, 1994.

I. Amato, "Plankton planet," *Discover,* vol. 25, 2004.

W.W. Charmichael, "The toxins of Cyanobacteria," *Scientific American,* vol. 270, pp. 78–86, 1994.

Glossary

Aerosolized—in the form of ultramicroscopic solid or liquid particles dispersed or suspended in air or gas.

Algae—small, single celled plants that grow in freshwater and oceans.

Ataxia—loss of the ability to coordinate muscular movement.

Autonomous underwater vehicles (AUV)—unmanned free-moving craft.

Bioaccumulate—the increase in concentration of a substance in an organism over time.

Dinoflagellates—any of numerous minute, chiefly marine protozoans of the order Dinoflagellata, characteristically having two flagella and a cellulose.

Gastroenteritis—an irritation and inflammation of the digestive tract.

Pantropical—found and/or distributed.

Phycotoxin—toxin produced by algae.

Trophic—pertaining to nutrition or to a position in a food web, food chain, or food pyramid.

Web Sites

www.noaa.gov

The National Oceanic and Atmospheric Administration homepage—This site provides access to a wealth of ocean-related data, from nautical maps to current ocean conditions.

http://www.whoi.edu/redtide/

The Harmful Algae Page—An overview of HABs, a description of HAB species, a discussion of possible effects, distribution maps of HABs, and current news are all provided on this Web site.

http://www.csc.noaa.gov/crs/habf/

NOAA's Harmful Algal Bloom Forecasting System Web Site—For the Gulf of Mexico, this Web site warns of possible HABs that are developing. The service was set up specifically to warn of potential *Karenia brevis* blooms and to help mitigate their impact

Pat Tester received her B.S. at California State University—Sonoma, and both her M.S. and Ph.D. degrees at the Oregon State University, School of Oceanography. Her work has focused on harmful algal blooms and their effect on the food web. She even had the opportunity to brief the Senate and House staff on harmful algal blooms and their potential impacts. In addition to science, she also enjoys hand spinning, weaving, and swimming.

NOTES:

Objectives

The objectives of these activities are

1. to learn about the biological and physical conditions that lead to a harmful algal bloom
2. to use real data to predict the fate of a harmful algal bloom
3. to research the causes of a recent harmful algal bloom

Materials

- Access to the Internet
- Access to newspapers/magazines

Background

Algal blooms only occur when a number of biological and physical factors come together in an ideal way for that particular species. Scientists use an equation to express this relationship:

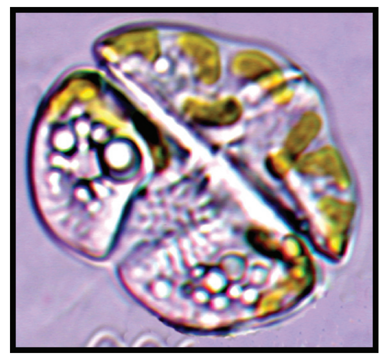
# of phytoplankton cells = growth of cells – loss of cells ± diffusion

Growth—The growth or photosynthesis of phytoplankton cells will depend on several factors. Most importantly, the phytoplankton cells must have access to sunlight and nutrients, as they use these as fuel for growth. In addition, the cells must be within an appropriate temperature range so it is not too hot or too cold.

Loss—Cell loss occurs mostly through grazing by predators or through viral infection, which can kill the cells. If the cells produce a toxin then the grazing rate on that type of cell may be dramatically reduced allowing it to grow much faster than any other species.

Diffusion—Phytoplankton do not live in a static environment—the ocean is always moving. These movements in the ocean can carry phytoplankton to new locations, concentrate the number of cells, or mix up a concentrated area causing a bloom to dissipate.

Activity #1



Karenia brevis Bloom

In the fall of 1987, a massive harmful algal bloom (HAB) occurred off the coast of North Carolina. It was caused by a phytoplankton species called *Karenia brevis*. Fisherman first noticed the bloom when the color of the water began to change. They also began to note respiratory problems and eye irritation. Over the course of the bloom, 48 cases of neurotoxic shellfish poisoning were reported. It also caused approximately 1,500 km^2 of shellfish beds to be closed and resulted in $24 million in economic losses. The bloom was particularly interesting from a scientific perspective in that a bloom of *K. brevis* had never been previously reported north of Florida! So, how did the bloom occur?

In performing their research, scientists discovered that there had been a bloom of *K. brevis* earlier in the season off the Florida coast. Would it be possible for the phytoplankton to travel from Florida to North Carolina, a distance of almost

700 miles (or 1180 km)? There is a current that runs up the East Coast of the United States from Florida called the Gulf Stream (Figure 1). Could the Gulf Stream carry phytoplankton for such a distance?

There are several pieces of evidence to support this interpretation. *K. brevis* are positively phototactic. This means that during the day they swim towards the sunlight, which tends to concentrate the cells at the ocean's surface. This behavior allows *K. brevis* to be moved more easily by winds and currents. Given the speed of the Gulf Stream, the bloom traveled from Florida to North Carolina in a reasonable amount of time. In addition, satellite images showed that in the beginning of autumn, waters from the Gulf Stream (a meander) came onto the continental shelf off of North Carolina. This provided a mechanism for the cells to be moved from Florida to the near-shore waters off the coast of North Carolina.

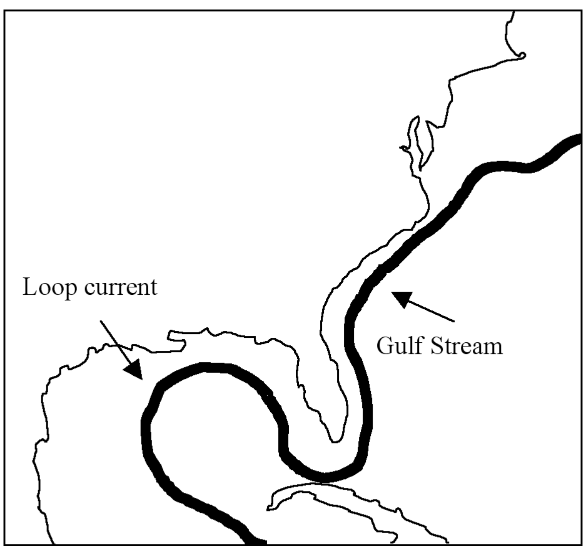


Figure 1. The average surface circulation for the Gulf of Mexico and East Coast is shown above. The Loop current moves into the Gulf of Mexico and moves clockwise around the Gulf. It leaves the Gulf south of Florida and becomes the Gulf Stream, which moves up the East Coast.

In this case, all of the conditions were optimized to allow *K. brevis* to increase to very high numbers near North Carolina. The phytoplankton were able to access light because they swam towards the surface and nutrients. The Gulf Stream water was warm, giving the phytoplankton the correct temperature range. Losses were apparently low. Although not directly studied, it can be assumed that grazing and viral infection were not major players. Perhaps the toxins produced by *K. brevis* decreased grazing rates. Finally, the physical conditions were such to allow transport from Florida. Only when all of these conditions came together would it be possible to get a bloom off the coast of North Carolina.

The above account was the only reported case of a *K. brevis* bloom off the North Carolina coast. *K. brevis* blooms occur nearly every year off the Florida coast. Why, then, has a bloom not made it to North Carolina since?

Procedure

1. Go to NOAA's Gulf of Mexico Harmful Algal Bloom Forcasting System Web site (current Web address: http://www.csc.noaa.gov/crs/habf/). This service provides alerts for HABs in the Gulf of Mexico to minimize possible human impacts.

What are the current conditions reported off the Florida coast?

2. Click on the "HAB bulletins" link. This page shows all of the bulletins that have been issued concerning possible HABs in the Gulf of Mexico since 2000.

Blooms of *K. brevis* can be transported by wind and also by currents. Using these bulletins, we can observe the movement of a *K. brevis* bloom. In November and December 2004, there was a well-defined bloom off of southwest Florida. Read through the HAB bulletins for 11/22/04 through 12/06/04. Each bulletin shows the movement of the bloom and the associated wind speed and direction. Does the bloom appear to move based on the prevailing winds? Explain and provide examples.

What was the overall distance the bloom was transported in the 14 days?

3. If there is a bloom in the Gulf of Mexico today, which direction would the winds need to blow in order for the bloom to be blown to shore? (If no bloom is present today, which direction would the winds have had to blow on December 6, 2004 in order for the bloom to be picked up by the Loop Current/Gulf Stream?)

4. Go to NOAA's National Data Buoy Center (current Web address: http://www.ndbc.noaa.gov/). This Web site provides current data of atmospheric and water conditions from buoys throughout the world. Choose the region including the area of the current HAB. Then choose the buoy closest to the current HAB. Are the winds blowing the correct direction to move the bloom to shore?

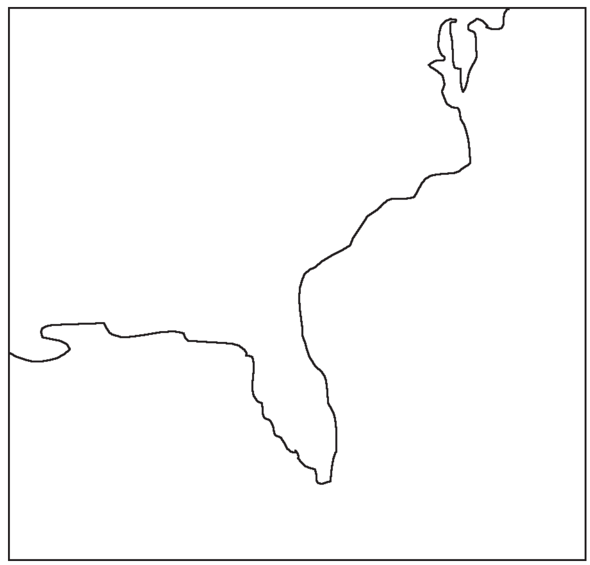
Yes / No

Wind direction:

Wind speed:

5. If the bloom were able to enter the Loop Current/Gulf Stream, estimate how long it would take for the bloom to be transported from its current location in Florida to North Carolina? (Assume an average speed of 35–85 km/d for the Loop current and the Gulf Stream, and an average distance of approximately 100 km for each degree of latitude and longitude.)

6. Go to the Applied Physics Laboratory's (APL's) Ocean Remote Sensing Web page (current Web address: http://fermi.jhuapl.edu/avhrr/). This Web site provides current and historical satellite images of the Gulf of Mexico/Gulf Stream region. The images provided are representations of sea surface temperature (SST). Warmer colors are shown in red and cooler colors are shown in purple. Because the Gulf Stream carries warm water northwards, it can be seen as a red "river" flowing within the ocean. View a current 7-day composite of the Gulf Stream and of the southern Gulf Stream (which shows the North Carolina region with higher resolution). Sketch the current path of the Gulf Stream.



7. Look in the archives for other images of the southern Gulf Stream. Can you find instances where the Gulf Stream came closer to the North Carolina shore?

Further from the NC shore?

Based on these images, do you think it likely that the Gulf Stream could transport *K. brevis* to the coast based on today's location of the Gulf Stream?

8. Go back to NOAA's National Data Buoy Center (current Web address: http://www.ndbc.noaa.gov/). Choose the region including North Carolina. What is the current

water temperature at station 41025, a station off the North Carolina Coast?

Current temperature:

K. brevis lives best at temperatures between 18 and 30°C. Based on temperature, could *K. brevis* be present in North Carolina waters today?

Yes / No

9. What other factors may also be important in influencing whether or not a bloom of *K. brevis* occurs?

Questions

1. Why do you think that only one bloom of *K. brevis* has occurred off the coast of North Carolina?
2. How could scientists monitor the waters off North Carolina to warn the citizens if a *K. brevis* bloom could potentially occur?

Information for this activity was provided by Patricia Tester and the following articles:

P.A. Tester, and K.A. Steidinger, "*Gymnodinium breve* red tide blooms: Initiation, transport, and consequences of surface circulation," *Limnology and Oceanography,* vol. 42, pp. 1039–1051, 1997.

P.A. Tester, R.P. Stumpf, F.M. Vukovich, P.K. Fowler, and J.T. Turner, "An expatriate red tide bloom: Transport, distribution, and persistance," *Limnology and Oceanography*, vol. 36, pp. 1053–1061, 1991.

Activity #2

Everyday in the newspaper there are articles relating to science and technology. Reading science articles is a very important skill to develop as it allows you to stay current on the ever-changing world of science.

Procedure

Harmful algal blooms are observed every year off the coast of the U.S. Look through newspaper or magazine articles and on the Internet to research an HAB that occurred in the last year and answer the following questions.

Questions

1. Where did the bloom occur?
2. What species was involved in the bloom?
3. Have similar blooms occurred in previous years?
4. What biological and physical conditions may have occurred to allow the bloom to develop (growth, losses, physics)?
5. Does the species produce a toxin? If so, what toxin? How does the toxin enter the body? What are the symptoms?
6. Were fish, marine mammals, birds or people effected by the bloom? If so, how?
7. What were the economic consequences of the bloom?
8. If you were a scientist, what aspect of the bloom would you study to help minimize the impacts of future blooms?

Oscar M. Schofield, Scott M. Glenn, Robert Chant, Josh Kohut, and Janice McDonnell

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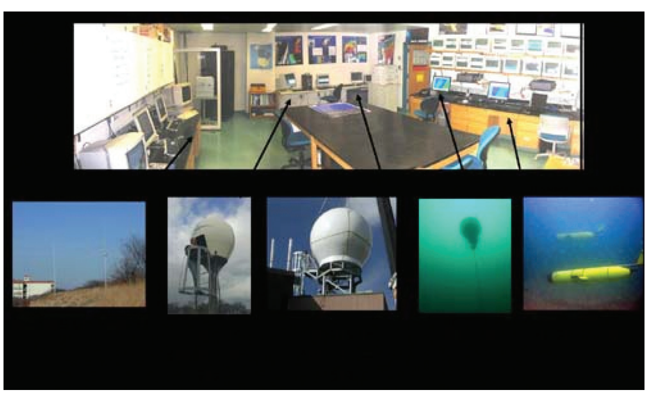
The world's continental shelves—the narrow ribbon between the major land masses and the deep ocean basins—cover only about 10% of the surface of the Earth, but are some of the world's most productive ecosystems and are home to most of the world's fish species. Across these continental shelves, sediments and chemicals supplied by rivers and beaches are transformed as they travel to the deep sea moving material into the deep ocean basins where it will remain for thousands to millions of years. These transport pathways are influenced by winds from the atmosphere pushing water at the surface ocean, currents from the deep ocean on the offshore side, and freshwater inputs from the inshore side. The biology and chemistry is continually changing as the water is transported. Understanding all these processes is extremely difficult. Historically, oceanographers use ships to study these processes; however, ships are slow, moving at the speed of a 10-speed bicycle, and therefore, it is difficult to collect the data that is required.



Developing new approaches to study the ocean is now especially critical. Human populations continue to grow and concentrate along the coasts. Globally, human activity is increasing the atmospheric concentrations of carbon dioxide, nitrogen, and other elements. Locally, we require food, water, and energy; protection from severe weather; and we produce waste. Continental shelves are affected by these increasing human pressures, responding both to the cycles and trends of global climate, and to the local needs and impacts of expanding coastal populations. Quoting the U.S. Commission on Ocean Policy, we need "sound science for wise decisions" to ensure the sustainable use of our coastal oceans for this and future generations. These needs have motivated many to start building integrated ocean observatories to study the ocean. One such observatory that has been developed is the Coastal Ocean Observation Lab (COOL).

COOL is an integrated network that was developed to allow scientists, environmental managers, and society to maintain a continuous presence in the ocean. The goal is to develop, demonstrate, and deploy the technologies that will allow humans to explore the oceans for sustained periods of time whether they are in New Jersey, California, Kansas, or another country. The goal is to ultimately develop a global capability. The COOL system currently consists of several technologies (Figures 1 and 2). Data is collected from 1) the international constellation of satellites used to measure the physics, chemistry, and biology of the ocean; 2) radar networks, which continually measure the surface currents for the entire continental shelf; 3) propeller-driven underwater robotic vehicles, which patrol the ocean collecting data; 4) sea-floor instrument packages, which are connected by cables that allow data to be instantly delivered back to shore; and 5) a fleet of unmanned smart robotic gliders, which can remain at sea for months at a time. These advanced technologies are then coupled to models which can be used to forecast the future and study "why" something happens in the ocean. The data from all these technologies are delivered back to a shore-based laboratory and immediately delivered to the world via the World Wide Web. This is a big step forward, as just a few years ago, it took months to years before ocean data collected by scientific instruments could be delivered to anybody.

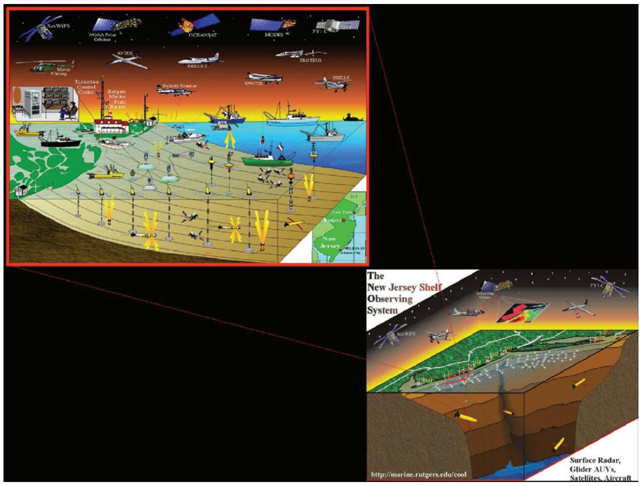


Figure 1. Overview of technologies involved in the COOL Room Observing network.

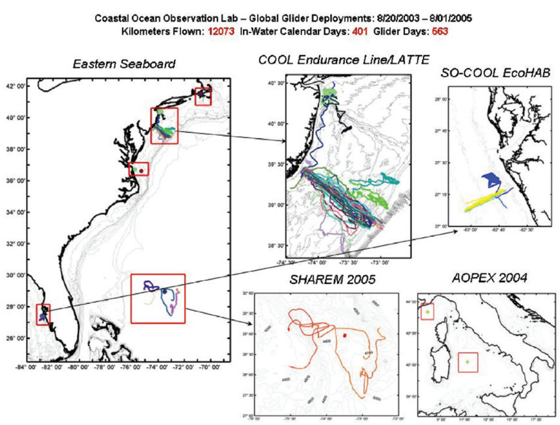


Figure 2. Locations where COOL ocean robots have been flying.

The goal is to explore the oceans and allow people to make smart decisions regarding the ocean. Decisions are being made everyday on a range of topics and scales. Where should I go fishing today? When should I bring my ships into port? Should we build offshore wind farms to contribute to the energy grid? Where will the hurricane make landfall? Where should my growing municipality locate its outfall? How should our nation respond to rising greenhouse gases? Wise decisions are based on some type of prediction, ranging from experience-driven rules-of-thumb to complex model results. Most predictions, in turn, are based on two types of information, an observation of our present state, and an understanding of the processes that will evolve that state into the future. Predictions as simple as "red sky at night, sailors delight," or as complex as weather forecasts that require an initial condition and a mathematical description of the laws of physics, illustrate the overarching need for both observation and understanding to make predictions.

Provided below are two examples highlighting the complex processes of coastal circulation.

Example 1: Buoyant plumes and material transport from the land to the deep sea. Buoyant coastal currents extend along much of the U.S. East Coast and are fed by numerous rivers. These buoyant plumes appear to dominate the transport of nutrients and chemical contaminants to the coastal ocean. This is especially true for the New York and New Jersey Harbor, which arguably holds the distinction of being one of the most contaminated estuaries on the East Coast. Therefore, understanding the transport of sediment and the associated material from the harbor to the coastal ocean is a fundamental problem for state and Federal water quality managers, a difficult task considering how dynamic these plumes are in space and time. These plumes are modified by bottom topography (shape of the sea floor), shoreline geometry, atmospheric conditions, tides, and river outflow. This makes sampling a plume using moorings impractical.

To monitor and adaptively sample the plume, scientists use the ocean observatory. The real-time data from all remote technologies are used to direct ships and gliders. Ocean color satellite imagery and sea surface temperature provide maps that help define where the Hudson River plume is. These satellite snapshots are then moved forward in time using the measured surface currents and simple models. The data and the forecasts are compiled in real time in the COOL room and then transferred to scientists working on ships at sea. This allows ships and roving fleets of ocean robots to adjust sampling strategies on the fly. Here, the scientist benefits from having a three-dimensional picture of the plume and its contents over a time period that is sufficiently long enough to study the transformation of organic material. The environmental managers benefit from a real-time picture of the plume allowing adaptive sampling and increased understanding of potential deposit centers of pollutants, heavy metals, organic and inorganic particulates flowing out of the harbor.

Example 2: Shelf circulation, and search and rescue. The spatial variability in continental shelf circulation is well known; however, until recently, the lack of data forced scientists, the Coast Guard, the Navy, and HazMat response groups to assume circulation was constant (5 cm/s water flow to the south). Measurements made by a High Frequency (HF) radar system uses radio waves to remotely measure ocean surface currents as far out as 200 km offshore. Surface current maps are now provided hourly, which indicate the directions and speeds of the current. These maps have great potential for search and rescue. Demonstration projects are being conducted to see if these surface current maps can help in Coast Guard search and rescue operations. This effort uses the existing HF Radar network off the coast of New Jersey (operated by the COOL room) and near the mouth of Long Island Sound (operated by the Universities of Connecticut and Rhode Island). Drifting buoys are used to simulate boats (or bodies) adrift at sea and search areas are defined with and without the use of Coastal Ocean Dynamics Applications Radar (CODAR).

These networks will transform how oceanographic research is conducted so this a very exciting time for oceanography. We are ready to tackle scientific problems that have challenged oceanographers for centuries while simultaneously serving the society that supports ocean research. The continued development of long-term monitoring, adaptive sampling, and dynamic forecast systems will especially enhance our understanding of the processes occurring on continental shelves, which are dynamic in space and time, and difficult to sample using traditional techniques. The importance and urgency of the research combined with the adventure of being at sea, makes for a rich life. This adventure will, in the next few years, be available to all and based on our experiences, we will all be richer for it.

Additional Reading

M. Carlowicz,. "The new wave of coastal ocean observing," *Oceanus,* vol. 43(1), 2004.

S. Gallager. "Sensors to make sense of the sea," *Oceanus,* vol. 43(2), 2004.

R. Geyer. "Where the rivers meet the sea," *Oceanus,* vol. 43(1), 2004.

Web Sites

http://www.thecoolroom.org/

The official COOL Room Web site by Rutgers University Coastal Ocean Observation Lab: This Web site will allow access to the data described in this article.

http://marine.rutgers.edu/neos/

The NorthEast Observing System (NEOS): Real-time and archived data are available from observing stations throughout the entire Northeast United States

http://www.csc.noaa.gov/coos/

Glossary

Buoyant—having the quality of rising or floating in a fluid; tending to rise or float.

Topography—the surface features of an object or how it looks its texture, direct relation between these features and materials properties (hardness, reflectivity etc.).

Moorings—equipment, such as anchors or chains, for holding fast a vessel or oceanographic equipment.

Real-time data—data that relates to systems that update information at the same rate as they receive data, enabling them to direct or control a process.

Organic—pertaining to carbon-based compounds produced by living plants, animals or by synthetic processes.

Inorganic—pertaining to substances not of organic origin.

National Oceanic and Atmospheric Administration Coastal Services Center: NOAA provides access to data from observing systems for the entire United States coastline. Data come from diverse technologies including buoys, bottom instruments, ship surveys, satellites, and autonomously operated vehicles.

COOL Room Further Reading

Related articles about coastal ocean environments:

Staying on Top: These Shoes Just Did It

http://seawifs.gsfc.nasa.gov/OCEAN_PLANET/HTML/oceanography_currents_2.html

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Introduction

As the hurricane season of 2005 clearly showed, predicting the path of tropical storms can be tricky. Inaccurate data can throw off a forecast by miles. Because it costs a community about $1 million a mile to evacuate its residents and visitors, knowing more precisely where a hurricane will make landfall could save hundreds of millions of dollars and allow rescue personnel to concentrate their resources on the hardest-hit areas [1].

The solution lies in creating a more reliable method of gathering *in situ* measurements of ocean surface winds, air temperatures, water salinity, and currents—factors that influence Atlantic storms. Unfortunately, gathering information on the open ocean presents big challenges and risks to scientists. As a result, while tens of thousands of observations are taken on land, only hundreds are taken on the ocean.

Part of the problem lies with the tools used to gather this all-important data, which are fed into supercomputers that then analyze the information and predict a hurricane's intensity and direction. The most commonly used techniques today include stationary or drifting buoys, research ships, and remotely sensed data collected by satellites, aircraft, and low-cost sensor packages. However, none is perfect for finding out conditions on the open seas.

For example, buoys that drift with the currents are short-lived and cannot be recovered, and those that are anchored to one spot are expensive to deploy, maintain, and redeploy—requiring a large number of people and vessels for the task. Research ships can cost from a few thousand dollars a day for coastal monitoring to $15,000 or more for ocean-class surveillance. Add up the numbers and this solution quickly becomes cost prohibitive.

Although satellites offer the advantage of gathering a larger amount of data, they often carry sensors that cannot see through clouds—a significant obstacle when dealing with hurricanes and other weather-related phenomena.

Given the physical and technical difficulties now hampering efforts to collect more precise and timely data, the National Aeronautics and Space Administration (NASA) joined forces with the National Oceanic and Atmospheric Administration (NOAA) to create a new system for collecting *in situ* ocean data using an autonomous ocean vessel. Recent demonstrations have proven the promise of these developing technologies.

Ocean–Atmosphere Sensor Integration System (OASIS)

At the heart of the research and development program is the Ocean–Atmosphere Sensor Integration System (OASIS) platform, a low-cost, self-navigating platform developed at the Wallops Flight Facility in Virginia, with significant funding from NOAA.

As designed by NASA, scientists would equip these unmanned surface vehicles with a range of instruments and sensors and deploy them from land or from small research vessels operating along coastal waters. The solar-powered platforms would travel at speeds of up to 2.5 knots (the speed of the fastest ocean currents and 10 times the average speed for ocean currents) to the targeted destination. Upon arrival at their destination, they would carry out their measurements, transmit and receive data by way of their real-time, two-way, Iridium satellite-based communication systems, and then return to their home base for refurbishment and calibration once they completed their observations. The hull of the vessel was specifically designed to survive hurricane conditions.

Currently, a commercial version of the platform is being developed to allow for rapid fabrication of a small fleet. Developers of the platforms at NASA purposely used off-the-shelf parts to keep down costs, and the platforms are likely to be available for about $80,000 for low fabrication numbers.

Adaptive Sensor Fleet (ASF)

Although the OASIS platforms can operate independently, software engineers at the Goddard Space Flight Center in Greenbelt, MD, have developed a technology that is ideal for controlling them.

The Adaptive Sensor Fleet (ASF) is a measurement software system that can guide fleets of data-gathering platforms—such as OASIS—as well as Mars-type rovers and eventually, unmanned aircraft to areas where scientists need up-to-the-minute information about local environmental conditions. With ASF, scientists define what they want to observe and the measurements they want to gather; the system analyzes the mission and recommends the best arrangement of platforms to carry out the task. The system's "fleet manager" then divides the work among the different ASF-equipped platforms, ideally using all platforms in the fleet to handle the mission.

Throughout the operation, the system communicates with the platforms, sends commands to the individual instruments and sensors in the fleet, and receives *in situ* measurements from the platform instruments. Scientists simply monitor the platforms' progress as they travel to the site and began gathering data. In other words, they have little or no interaction with the system once they input their mission requirements.

At a recent demonstration at the Goddard Space Flight Center, ASF designers used three small robots operating in a simulated Martian landscape to show the technology's capabilities. After programming target and data requirements into the system, the inventors watched as the fleet manager took charge. It distributed data-gathering assignments, determined the routes, and modified instructions if the rovers encountered obstacles. As the robots advanced to their target, the software system displayed the rovers' progress and their cumulative scientific data on a computer screen.

Ideal for Meteorological Purposes

Although ASF team members demonstrated the technology on a simulated Martian surface to show its applicability to space exploration, they believe the technology has wider use on Earth in the near term—particularly in the area of ocean studies.

Used in conjunction with other measurement assets, including satellites, ASF-equipped OASIS platforms could gather more precise, up-to-the-minute ocean surface and subsurface data needed for hurricane forecasting models. The availability of more data would make a significant difference. Because of measurement inaccuracies and too few observations, meteorologists now consider a good forecast to be one that gets the location of a hurricane to within 50 miles and wind speeds to within 8 mph, 12 hours before the storm makes landfall [2]. When evacuating citizens, however, 50 miles is a large area to cover. Because OASIS is fully autonomous, unlike the traditional fixed buoys that are logistically demanding to move and drifters whose paths cannot be controlled, it can be redeployed easily to carry out observations in other ocean regions and all from a desktop computer.

Other Applications

The technologies have other applications, too. In addition to sending the platforms to study hurricanes, environmental organizations could use ASF-equipped OASIS platforms to monitor the health of important coastal areas. In fact, such a demonstration is scheduled to occur along the coasts of Virginia, Maryland, and Delaware. There, researchers hope to monitor the influence of the Chesapeake Bay and adjacent coastal ecosystems. A NASA-funded effort with Carnegie Mellon University is now underway to use OASIS platforms to map and monitor harmful algal blooms.

The Future

The creators of both OASIS and ASF say they will continue to fine-tune their technologies and demonstrate their usefulness under different research environments. Used together or separately, ASF and OASIS could help scientists with everything from tracking killer storms and algal blooms on Earth to navigating rovers on the Moon or Mars.

Acknowledgments

We would like to thank both NASA and NOAA for their continued support of our research.

Additional Reading

M. Yarosh and T. Vagoun, “CoastalObs Tests the Waters in the Chesapeake Bay,” *Sea Technology,* 47(9), 27–29, 2006.

C.J. Koblinsky and N. Smith (eds), *Observing the Oceans in the 21st Century,* Global Ocean Data Assimilation Experiment (GODAE) Project Office, 2001.

D.L. Rudnick and M.J. Perry, (eds.), *ALPS: Autonomous and Lagrangian Platforms and Sensors,* Workshop Report, 64 pp., www.geo-prose.com/ALPS, 2003.

T. Ames, J, Moisan, P. Pittman. *Ocean–Atmosphere Sensor Integration System (OASIS) Prototype Report,* NASA Goddard Space Flight Center, Greenbelt, MD, 2003.

A.E. Bryson, Jr., and Y-C. Ho, *Applied Optimal Control.* Hemisphere Publishing Company, New York, 1975.

Web Sites

For more information about NASA’s Adaptive Sensor Fleet Technology:

http://aaaprod.gsfc.nasa.gov/Website/ViewPage.cfm?selectedPage=64&selectedType=Project

References

[1] J. Whitehead, *One Million Dollars a Mile? The Opportunity Costs of Hurricane Evacuation,* Department of Economics, East Carolina University, Greenville, NC, March 2000.

[2] National Oceanic and Atmospheric Administration Web Site: http://hurricanes.noaa.gov/prepare/title_uncertainty.htm.

Biographical Sketches

John Moisan: Dr. Moisan received a B.S. in Marine Biology from the University of New England and a Ph.D. in Physical Oceanography from Old Dominion University. Before coming to NASA in 2000, he was employed as a post-doc at the Scripps Institution of Oceanography and also as an Assistant Professor at Long Island University. His research focus is on developing coupled circulation-biogeochemical models and in developing new sensors for studying the ocean autonomously.

Jeffrey Hosler: Mr. Hosler received a B.S. in Computer Science with Aviation Applications from Embry-Riddle Aeronautical University. Over the past six years, as a software R&D manager at the Goddard Space Flight Center in Greenbelt, MD, he has

Glossary

Autonomous—operating independently or alone.

Buoy—an anchored float equipped with scientific instruments and sensors.

Fabrication—the act of constructing something from raw materials.

In situ—Latin phrase meaning “in its original place.”

Knot—a unit of measurement for the speed at which a ship or aircraft travels (nautical miles per hour).

Meteorologists—people who study Earth’s climate and weather.

Sensors—devices capable of detecting physical conditions, such as light and heat.

Salinity—the amount of salt in a body of water.

explored cutting-edge technologies in distributed architectures, sensor webs, fleet control, path planning, agent-based systems, and Web technologies. Goddard has incorporated the research into its Mission Services Evolution Center and used it as the basis for other research.

To access the answer keys to all activity and discussion questions found throughout this journal, please visit the "*Rising Tides* Teacher Resource Section" at the following Web site:

"Foundations of Phytoplankton"—http://phytoplankton.gsfc.nasa.gov

On a scale of 1–5, 1 being the least, 5 being the most, please rate questions #1–6. All questions are based on the first five articles of the journal; please do not consider the Advanced Section. Please complete items #7–10. A section follows for comments and questions you may have after item #10

1. Readability for high school or college grade level? 1…..2…..3…..4…..5
2. Length of articles appropriate to hold interest? 1…..2…..3…..4…..5
3. Content appropriate for curriculum requirements? 1…..2…..3…..4…..5
4. Activities appropriate length? 1…..2…..3…..4…..5
5. Usefulness of activities? 1…..2…..3…..4…..5
6. Number of articles you actually used from this journal? 1…..2…..3…..4…..5
7. Prep time necessary to prepare for the lesson? ½ hour…1 hour…2 hours…too long
8. Grade level and course taught: ______________________________
9. Name: ______________________________
10. Address: ______________________________

Suggestions to improve the next edition:

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Brian A. Campbell
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1.	Readability for high school or college grade level?	1. . ...2. . ...3. . ...4. 5
2.	Length of articles appropriate to hold interest?	1. . ...2. . ...3. . ...4. 5
3.	Content appropriate for your course?	1. . ...2. . ...3. . ...4. 5
4.	Activities appropriate length for your class time?	1. . ...2. . ...3. . ...4. 5
5.	Clear directions for activities?	1. . ...2. . ...3. . ...4. 5
6.	Number of articles you actually used from this journal?	1. . ...2. . ...3. . ...4. 5
7.	Time necessary to complete the lesson?	½ hour. . .1 hour. . .2 hours. . .too long

8. Grade level and course: ______________________________

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